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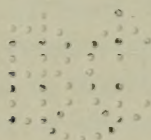
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PREFACE

THE efficient operation and control of Steam Boiler and Furnace Plants calls for a knowledge of the principles of combustion and of the requirements of different fuels and different types of furnaces.

Although many articles have appeared from time to time dealing with individual questions connected with the operation of Steam Boilers, the authors think that it will be of considerable interest to many engineers to have the various factors which play an important part in the efficient working of a furnace set out in a convenient manner for reference.

The question of smoke prevention is now of great importance owing to the steps which are being taken in many quarters to reduce the nuisance caused by the emission of black smoke. Smoke is a sign of inefficient combustion and represents a direct loss of fuel, and is, therefore, to be deprecated both from the point of efficiency of the plant and of the nuisance caused to the surrounding neighbourhood by the deposition of soot. A further trouble in many boiler plants which are being worked at high rates of combustion is the emission of grit from the chimney, and various methods are now being developed for preventing this emission.

In the present volume the authors have dealt more particularly with the question of combustion as affecting the various classes of fuel in general use, from a practical, as well as a theoretical point of view, while in the companion volume—

“Mechanical Draught,” the various systems employed for producing and controlling the supply of air to the grates of steam boiler and other furnaces will be dealt with.

Figures have been published recently of tests on a large number of industrial boiler plants which show that the average efficiency is only about 50 per cent. to 55 per cent., and as the modern boiler plant can show an efficiency of 80 per cent. to 85 per cent. when properly worked, there is a considerable margin of loss which can be largely prevented by the adoption of proper methods of control.

To ensure efficient combustion it is necessary to know what is happening in the furnace and the flues, and for this various instruments are required. Such instruments may range from a simple draught gauge to a complete installation of recorders from which practically everything that takes place in the system can be seen with a very close degree of accuracy.

A complete set of instruments of this kind may cost a large sum, but if used intelligently they enable a saving in fuel to be made many times greater than their initial cost.

The authors hope that the information given in this volume will prove of interest and assistance to many who are concerned with the control of furnaces or steam boilers.

J. E. L.

C. H. H.

May 1925.

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THE THEORY AND PRACTICE OF COMBUSTION

CHAPTER I

COMBUSTION

COMBUSTION is generally understood to mean the union of various substances with oxygen by chemical action and with evolution of heat and, generally, light, though in some cases the combination may proceed so slowly that the production of light is not noticeable.

The most important combustible, for general purposes, is carbon in one or other of its widely occurring forms. Carbon is the most important constituent of coal, wood, oil, peat, coke and gas, and these substances are therefore the most useful and most commonly used fuels.

Coal is now being replaced for many purposes by oil and gas, which offer various advantages in actual use, but coal is still by far the most largely used fuel, and the majority of boiler and other furnaces are constructed for its use.

The oxygen which is required for combustion is usually found in small quantities in the fuel, but the greater part is derived from the atmosphere, where it is present in very large quantities in association with nitrogen. In the fuel, the small proportion of oxygen is generally in chemical combination with one or other of the constituents, but air is only a mechanical mixture of oxygen

with approximately four times its volume of the inert gas nitrogen, together with small quantities of carbon dioxide, aqueous vapour and other impurities.

The proportion by weight is approximately :—

Oxygen . . . 23·2 per cent.

Nitrogen . . . 76·8 „ „

All chemical combinations have been found to take place in definite and fixed proportions, though in many cases there are two or more different combinations of the same substances in varying proportions.

Until the recent development of the electron theory of matter it was generally accepted that an atom was the smallest particle into which matter could be divided, while a molecule, which is the result of a combination of atoms, is the smallest particle which can exist in the free state.

The atomic theory forms a very convenient means of ascertaining the relative weights of the various combinations formed during the process of combustion as the relative atomic weights of the constituents of the fuel are known. It is generally assumed that the atoms are all of equal size and the atomic weights represent the specific density of the various elements referred to hydrogen, which is the lightest known element, as unity.

The chemical formula for any substance indicates the elements entering into combination, and the number of atoms of each element present are designated, where the number is more than unity,

by a suffix numeral. Thus H_2O , the chemical symbol for water, indicates that two atoms of hydrogen have combined with one atom of oxygen to form one molecule of water. It is found by experiment that this volume of water, if present as vapour, occupies exactly the same space as the two atoms of hydrogen, hence, taking the atomic weight of hydrogen as 1, and that of oxygen as 16, the density of the aqueous vapour will be $\frac{2 + 16}{2} = 9$.

Similarly, the relative density of other gases can be determined by ascertaining their chemical composition and combining the atomic weights of the elements in a similar manner.

The symbols and atomic weights of the various elements present in fuels are given in Table I.

TABLE I.

Element.	Symbol.	Atomic weight.
Hydrogen	H	1
Carbon	C	12
Nitrogen	N	14
Oxygen	O	16
Sulphur	S	32

In addition there may be present small amounts of silica and other impurities which form an ash and do not enter into the reactions which evolve heat.

As mentioned above, many substances can combine in more than one proportion. Carbon, the principal constituent of fuels, can in this way combine with two different proportions of oxygen.

In the first place, one atom of carbon will unite with one atom of oxygen, forming carbon monoxide, represented by the symbol CO, the percentage composition being C, 42·86, O, 57·14. This reaction is incomplete and can only take place where there is an insufficient supply of oxygen. If there is an excess of oxygen, the atom of carbon will unite with two atoms of oxygen, forming carbon dioxide, represented by the symbol CO₂, with a percentage composition of C, 27·27, O, 72·73.

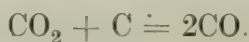
In the first case, the heat evolved by the combustion of a pound of carbon is approximately 4400 British Thermal Units, whereas when the combustion is complete the heat evolved amounts to 14,650 B.Th.U. Hence for every pound of carbon which is only partly oxidised there is a definite loss of over 10,000 B.Th.U.

Both carbon monoxide and dioxide gases are transparent and colourless, but while CO is an actual poison, CO₂ is not poisonous, but will not support life nor combustion owing to the absence of free oxygen.

Carbon dioxide, in the presence of moisture, forms a weak acid which rapidly attacks steelwork.

Carbon monoxide may be formed from the dioxide by passing the latter through a zone of red-hot carbon, and this reaction forms the basis of the various producer plants employed for generating power gas.

The process may be represented by :—



Next to carbon, hydrogen is the most important constituent of fuels, as, although it is present in much smaller quantities, the heat generated by the combustion of a pound of hydrogen amounts to 62,100 B.Th.U. Sulphur is also present to a very small extent, but as its calorific value is only 4032 B.Th.U. per pound, it is generally neglected in practical calculations.

Nitrogen is inert and has no influence on the value of the fuel, while any oxygen present merely reduces the amount which must be supplied from the atmosphere.

The Chemical Process of Combustion.—The chemical processes which take place during the combustion of solid fuel are generally considered to be as follows.

When the fuel is first put into the fire the volatile constituents are driven off in the form of gases. This reaction is "endothermic," *i.e.*, heat is absorbed and is converted from the sensible to the latent form. The hydrogen present in the fuel as hydrocarbon combines with its proportion of oxygen to form steam, while the carbon combines with a further amount of oxygen to form either CO or CO₂, according to the amount of air admitted, though if the air supply is very much restricted some of the carbon will pass away unburnt.

The heat generated during this part of the reaction raises the temperature of all the gases, including the inert nitrogen and any free oxygen which remains.

It is important that the temperature in the

early part of the process be maintained at a high figure, not only on account of the cooling effect of the distillation process, but also on account of the fact that the hydrogen will not combine readily with the oxygen at temperatures below about 600°C ., while carbon requires a temperature of 800°C . for combustion.

Table II gives the temperature at which various combustibles will ignite in air.

TABLE II.

Combustible.	Ignition temperature.
Hydrogen	$1075\text{--}1100^{\circ}\text{F}$.
Carbon	$1470\text{--}1650^{\circ}\text{F}$.
Carbon monoxide	$1190\text{--}1197^{\circ}\text{F}$.
Methane	$1200\text{--}1380^{\circ}\text{F}$.
Ethylene	$975\text{--}985^{\circ}\text{F}$.
Acetylene	$730\text{--}790^{\circ}\text{F}$.

Some carbon monoxide is formed unavoidably during the passage of the CO_2 over the red-hot fuel, but this is again converted into the dioxide on meeting a further supply of heated oxygen.

As mentioned above, the heat evolved by the partial combustion of carbon to CO is very much less than that produced by its complete combustion, and it is therefore most important to produce the maximum of CO_2 and the minimum of CO, except in certain metallurgical furnaces, where a reducing flame is necessary. The presence of carbon monoxide is shown by a blue flame.

If the temperature of the fuel bed should fall below that necessary for the combination of the carbon and oxygen, some portion of the carbon

will pass off as black smoke. The higher the temperature the less surplus air will be required to ensure the complete combustion of the carbon. In many cases, considerable economy can be effected by preheating the air for combustion, as not only does this heating of the air supply assist in maintaining complete combustion, but the furnace is not called upon to raise the temperature of a considerable weight of cold air.

The amount of heat evolved is independent of the rate of combustion, though the actual temperature in the furnace will depend on the rate at which the heat is carried away by the boiler plates or brickwork surrounding the furnace.

Taking the figures given above for the heat evolved by the combustion of the principal constituents of fuel, the calorific value of any fuel may be calculated. It is assumed that the oxygen present is already in combination with hydrogen in the form of water, the amount of hydrogen so combined being, as explained above, one-eighth by weight of the oxygen. It is therefore necessary to deduct from the total weight of the hydrogen an amount equal to one-eighth of the weight of oxygen.

The calorific value is then given by :—

$$14,650C + 62,100(H - \frac{1}{8}O)$$

where C, H and O represent the weights of carbon, hydrogen and oxygen respectively in 1 pound of the fuel.

M. Scheurer-Kestner found that calorific values calculated in this way gave figures about 10 per

cent. less than he obtained with a calorimeter, but other experimenters have found the calculated figures higher than those given by actual test and for ordinary purposes the method of calculation given above may be taken as sufficiently accurate.

Marsh gas and olefiant gas are found as constituents in certain fuels, and these gases have calorific values of 23,513 and 21,343 B.Th.U. per pound respectively.

Air Required for Combustion.—The amount of air theoretically required for the complete combustion of 1 pound of hydrogen and of carbon can be calculated from a consideration of the chemical reactions.

As explained above, hydrogen and oxygen combine in the proportions of two atoms of H to one atom of O, while their atomic weights are respectively 1 and 16, hence the proportion by weight of the product, water, is as 1 to 8, *i.e.*, 1 pound of hydrogen requires for its complete combustion 8 pounds of oxygen.

Similarly, carbon will require 2.67 pounds of oxygen for its complete combustion to CO_2 .

From these figures the weight and volume of air required can be obtained. Air contains 23.2 per cent. by weight of oxygen, hence the weight of air required for burning 1 pound of hydrogen is

$$\frac{8}{0.232} = 34.48 \text{ pounds, and for 1 pound of carbon}$$

$$\frac{2.67}{0.232} = 11.5 \text{ pounds.}$$

One pound of air at 62° F. and normal barometric

pressure occupies a volume of 13·15 cubic feet, hence the volume of air required for the complete combustion of 1 pound of hydrogen = 469 cubic feet, and for 1 pound of carbon 156·5 cubic feet.

The various data regarding the principal constituents of fuels are summarised in Table III.

From the data given in Table III the approximate amount of air required for the combustion of 1 pound of any ordinary fuel, neglecting the sulphur, which is usually present in very small quantities only, may be taken as :—

$$\text{Wt. of air} = 11\cdot5 C + 34\cdot5 \left(H - \frac{O}{8} \right)$$

where C, H and O are the actual weights of carbon, hydrogen and oxygen in the pound of fuel.

For ordinary purposes it is quite sufficient to take the weight of air required for the combustion of 1 pound of coal or coke of reasonably good quality, as 12 pounds, and for 1 pound of oil as 16·5 pounds.

It is found in practice that it is necessary to supply a considerable excess of air in order to ensure that the whole of the combustible in the fuel comes in contact with sufficient oxygen to ensure combustion.

The excess air may range from 25 or 30 per cent. in furnaces using oil, gas or powdered fuel to 60 per cent., or even 100 per cent. in some cases, where air is supplied under natural draught to furnaces operating on solid fuel.

TABLE III.

Constituent.			Product of combustion.				Required for complete combustion—per pound.			
Name.,	Symb.	Atomic or molecular weight.	Density or weight of 1 cub. ft. pound.	Name.	Symb.	Atomic or molecular weight.	Density or weight of 1 cub. ft. pound.	Oxygen. pounds.	Air. pounds.	cub. ft.
Oxygen	O	16	0.08926	—	—	—	—	—	—	—
Nitrogen	N	14	0.07842	—	—	—	—	—	—	—
Hydrogen	H	1	0.00559	Water	H ₂ O	18	—	8.00	34.48	469
Carbon	C	12	—	Carbonic oxide	CO	28	0.07813	1.33	5.74	78
"	"	"	—	Carbonic acid	CO ₂	44	0.12343	2.67	11.5	156.5
Carbonic oxide	CO	28	0.07813	"	"	"	"	0.57	2.45	33.4
Marsh gas	CH ₄	16	0.04513	Water	H ₂ O	18	—	4.00	17.24	234
"	"	"	"	Carbonic acid	CO ₂	44	0.12343	—	—	—
Olefiant gas	C ₂ H ₄	28	0.07898	Water	H ₂ O	18	—	3.43	14.9	201
"	"	"	"	Carbonic acid	CO ₂	44	0.12343	—	—	—
Sulphur	S	32	—	Sulphurous acid	SO ₂	64	0.17851	1.00	4.31	58.6

The most economical quantity of air must be found by experience. Only the minimum excess required to ensure complete combustion should be permitted, as beyond this point a larger supply of air will reduce the temperature in the furnace, and it must not be overlooked that every pound of air admitted must be raised by some means or other from the temperature of the atmosphere to that of the furnace.

It is found that with ordinary furnaces the intensity of the draught has considerable influence on the amount of air required. Whereas with natural draught the excess of air required to effect complete combustion may be in the neighbourhood of 100 per cent., with a forced draught, produced by mechanical means, this excess may be reduced to about 50 per cent., hence the furnace temperature will be considerably higher, and in the case of steam boilers, to which these remarks are specially applicable, the efficiency of the boiler will be increased, due to the greater rate of transmission of heat from furnace to water at the higher temperature.

Also, the higher the temperature the more readily will the combustibles unite with the oxygen and the more complete will be the combustion.

The whole of the air should, as far as possible, be supplied through and over the grate or burner, or immediately at the rear of the grate in the combustion space. No air should be allowed to leak in through the flue walls, as this not only reduces the efficiency, but may lead to combustion in the

flues, where it is useless, if the combustion in the furnace has not been complete.

The process of combustion requires an appreciable time for its completion, hence the velocity of the gases should not be so great that combustion is not completed in the furnace, or, in the case of a boiler, before the gases leave the tubes.

In the case of furnaces burning pulverised fuel, oil and gas, it is easier to bring the atoms of fuel and oxygen into intimate contact than in the case where ordinary solid fuel is burnt, and a smaller excess of air is usually required for complete combustion. On account of this more intimate contact it is also possible to burn fuels of low calorific value which would offer difficulties in the solid condition.

Since the air supplied for the combustion of the fuel contains approximately 21 per cent. by volume of oxygen, if only just sufficient air were supplied and complete combustion were obtained, the percentage of CO_2 in the products of combustion, assuming the fuel to be pure carbon, would be 21 per cent. by volume, for, as explained above, the volume of a molecule of CO_2 is the same as that of a molecule of oxygen.

In actual practice, the percentage would not be quite so high, because of the proportion of hydrogen, sulphur, etc., which is always present, and the figure is generally taken as approximately 19. The percentage of CO_2 in the flue gases does, however, afford a very reliable guide to the excess of

air which is being admitted, and every effort should be made to keep this percentage at the highest possible figure without showing any appreciable amount of CO.

It has been suggested that it would be better to take the proportion of CO as a more reliable guide, maintaining this at a figure of about $\frac{1}{4}$ per cent., which indicates the most efficient proportion of air, with an occasional check of the CO₂ and oxygen to ensure that there is no leakage of air into the flues. The presence of this small proportion of CO indicates that there is no surplus air passing into the furnace.

Unless the analysis of the flue gases is known it is impossible to say whether the best furnace conditions are being obtained, though even without an analysis much may be done by careful firing to improve the working of the plant.

It has been shown that the theoretical maximum percentage of CO₂ is about 21. When it is realised that in many boiler installations the percentage of CO₂ obtained is as low as 8, 7 or even 6, it is obvious that in such cases a very great excess of air is being admitted, with a corresponding reduction in the furnace temperature and in the efficiency of the plant.

The following table gives the loss of heat for various percentages by volume of CO₂ in the flue gases, assuming the temperature of the air supplied for combustion as 65° F. and that of the flue gases as 515° F. :—

TABLE IV

Percentage CO ₂ in flue gases by vol.	1	2	3	4	5	6	7
Excess air, per cent.	1790	850	530	370	280	220	170
Heat loss, per cent.	180	90	60	45	36	30	26
Percentage CO ₂ in flue gases by vol.	8	9	10	11	12	13	14
Excess air, per cent.	140	110	90	70	60	50	40
Heat loss, per cent.	23	20	18	16	15	14	13

The excess of air given in this table is derived from the formula :—

$$\text{Percentage excess volume of air} = \left(\frac{19}{\% \text{ CO}_2} - 1 \right) 100.$$

The loss of heat can be calculated from the composition and calorific value of the fuel or from the analysis of the gases, but it can also be obtained approximately from a simple formula :—

$$H = K \frac{T - t}{\% \text{ CO}_2}$$

where T = temperature of flue gases.

t = temperature of air supply.

K = a coefficient = 0.65.

The gases to be analysed should, if possible, be taken from a point immediately at the back of the furnace, or, in the case of a tubular boiler with internal furnace, at the end of the tubes, before there is any chance of the proportions of the various constituents being altered by leakage of air into the brickwork of the settings.

Various methods of obtaining the analysis of the gas, and the types of instrument in general use, are described in a subsequent chapter.

With ordinary rates of combustion, it is unnecessary to run the fuel bed thicker than 4 inches to 6 inches to obtain a high CO_2 and low oxygen content in the flue gases, though in actual practice it is generally found necessary, by the limitations of stoking, to run the fire with a greater thickness

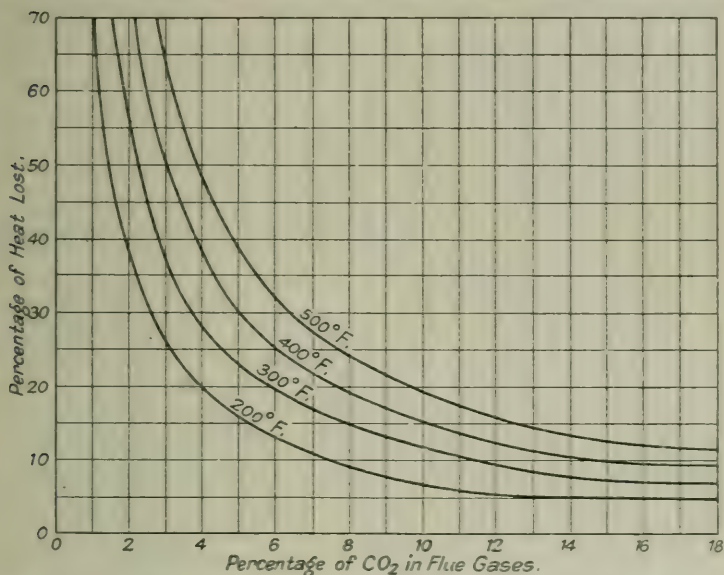


FIG. 1.—Diagram showing relation of CO_2 Content in Flue Gases and Heat Lost, for Various Temperature of Gases.

of fuel. To obtain complete combustion, half the air required may be supplied through the grate and half over the fuel bed.

Fig. 1 shows the relation between the percentage of CO_2 in the flue gases and the loss of heat for different flue-gas temperatures.

For ordinary boiler plants the best working results are generally found when the flue gases

contain from 10 to 15 per cent. of CO_2 , according to the class of coal in use, the design of the plant and other local conditions. For a plant which includes an economiser or air heater, the flue-gas temperature is generally about 400°F. , and it will be seen from the diagram that at this temperature, with a CO_2 content of 12 per cent., the heat lost up the chimney amounts to about 13 per cent. With only 8 per cent. of CO_2 , which is a figure often found in practice where boilers are not being worked to the best advantage, the heat lost amounts to about 19 per cent. Thus with a drop of only 4 per cent. in the CO_2 nearly 50 per cent. more heat is lost up the chimney.

At 500°F. the heat lost in the gases under similar conditions amounts to 16 and 24 per cent.

It is therefore evident that to keep the loss of heat to a minimum the temperature of the flue gases should be kept to the lowest possible figure, while the percentage of CO_2 should be kept to the maximum possible with no CO , or only the slightest possible percentage of this constituent.

The effect of the presence of unburnt gases in increasing the loss of heat is shown in Fig. 2. It will be seen that the loss increases very rapidly as soon as any CO appears in the flue gases, and it is therefore evident that increase of the CO_2 content should not be carried to such an extent that any considerable amount of CO is present.

The question of smoke production or elimination is closely bound up with the attainment of complete combustion.

Smoke has been for many years, and is still for certain metallurgical purposes, regarded as a necessary evil, but a very strong movement is now on foot to abolish it as far as possible, in view of its proved deleterious effects when present in any quantity.

It is not necessary to admit an excessive quantity

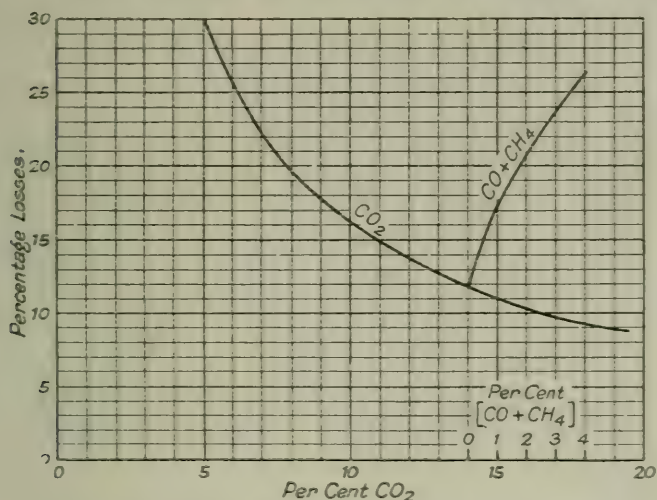


FIG. 2.—Losses of Heat due to Incomplete Combustion.

of air in order to prevent smoke, but the air must be admitted in the correct quantity and in the right place to ensure that no unburnt carbon is carried out by the flue gases.

As soon as fuel is introduced into a fire, combustion commences and the volatile constituents combine with the oxygen of the air to form CO_2 , if the supply of air is ample, or CO if the air supply is insufficient. This volatilisation process absorbs

heat, as mentioned previously, and if any of the volatile hydrocarbons are able to escape into a cooler part of the flue, where the temperature is insufficient to maintain combustion, they will be condensed and smoke will be formed. Fine particles of unconsumed carbon may also pass off as soot, together with the ash, which is combustible.

Some authorities consider that practically the whole of the smoke and soot is due to carbon formed in the furnace by the partial combustion of the hydrocarbons, and not to the solid particles of carbon from the fuel itself. This point of view is borne out by the fact that coke and anthracite, which contain very little of the volatile hydrocarbons, burn without smoke.

In any case, the production of smoke means inefficient combustion, and may be almost entirely prevented by the adoption of proper methods of operation.

The actual loss of carbon does not probably exceed 1 or 2 per cent. of the carbon in the fuel, and is not consequently very important economically, but the hygienic point of view must not be overlooked, and there are indirect losses which may reach an appreciable figure.

The collection of a layer of soot and ash on the flues and tubes of boilers considerably increases the resistance to the transmission of heat from furnace to water, a thin layer only being required to reduce the efficiency of the boiler by 2 or 3 per cent.

The formation of smoke is prevented by (1) the admission of an adequate supply of air, (2) the thorough admixture of this air with the gases, and (3) the maintenance of a temperature sufficiently high to ensure the complete combustion of the carbon as well as the hydrogen.

Hand stoking is responsible for the greater part of the black smoke seen coming from boiler chimneys, and is due mainly to careless or irregular firing. If the fire be allowed to become too thin and a large amount of coal is thrown on to bring up the fire to its normal thickness, the fire is chilled and a considerable amount of carbon escapes unburnt. Unless the fire is maintained of even thickness large volumes of air will rush through the thin places, with a deficiency through the thicker portions, and combustion will again be irregular, with the consequent formation of smoke.

To avoid this irregular combustion, one of two methods should be employed in hand-fired furnaces. In the first method, the coal is fired on to the dead plate just inside the furnace door. In this position the coal is partly distilled and the gases evolved are burnt during their passage over the glowing fuel in the main part of the furnace. This partly-coked fuel is then pushed forward to maintain the thickness of the fire on the bars and its place taken by fresh coal.

In the second method, the fuel is fired alternately on one side of the fire and then on the other, sufficient time being allowed to elapse for the new fuel to become fully incandescent before a fresh

supply is thrown on to the other half of the fire.

A third method is sometimes adopted, coal being fired in a thin layer over the whole of the fire at once, but this plan is rather more liable to produce smoke than the other two methods.

Automatic stokers are not so liable to produce smoke, as the fuel is fed on to the fire more regularly and a fire of even thickness is more easily maintained. A description of various types of automatic stokers is given in a subsequent chapter.

As mentioned previously, it is necessary to introduce part of the air above the fire or round the burner in order to ensure complete combustion, and an auxiliary supply is sometimes introduced also at the bridge at the back of the furnace, to meet any gases that may be leaving the furnace unconsumed.

In some cases an automatic arrangement is adopted whereby a supplementary supply of air is admitted at the bridge whenever the furnace door is opened. This arrangement is said to be effective in reducing the production of black smoke. The admission of preheated instead of cold air is also useful, as the temperature of the furnace is not reduced to so great an extent.

The most effective method of eliminating smoke is the use of fuel in a gaseous form. With this type of fuel the admixture of air can be very closely regulated, and practically perfect combustion obtained. Gases, such as ordinary town's gas, producer gas, and, where they can be obtained,

the waste gases from blast furnaces and coke ovens, are now in extensive use, and they offer many advantages in cleanliness of working and the ease with which the temperatures may be controlled.

Pulverised coal is also being largely adopted at the present time, and in this case also combustion can be closely regulated and the production of smoke prevented.

CHAPTER II

TEMPERATURE OF COMBUSTION

IN many combustion problems it is essential to maintain a predetermined temperature, while in the case of steam boilers it is important to maintain a high temperature, as it is found that the transmission of heat through the boiler plates or tubes is much more rapid at high temperatures, and falls off considerably as the temperature of the gases is reduced in their passage through the boiler. It is therefore necessary to know the temperature that may be expected from the combustion of any fuel.

The theoretical temperature of combustion may be calculated from a knowledge of the total and specific heats of the combustibles and of the products of combustion. It is, of course, impossible to obtain this figure on account of unavoidable losses, and the furnace temperature must therefore be less than its theoretical value. It is consequently important to reduce the losses to a minimum by all possible means, such as the use of good heat insulating materials and the prevention of avoidable air leakage.

The total heat of combustion is determined by means of a Calorimeter, either of the closed or bomb type, or of the Mahler pattern.

The table on page 35 gives the total heat of combustion, in British Thermal Units, of the principal fuel constituents, and of various fuels of average quality, with their equivalent value in carbon.

TABLE V

Calorific Power, Carbon Value and Evaporative Power of Various Fuels

Combustible.	Calorific power in B.Th.U.	Carbon value.	Evaporative power in pounds of water from and at 212° F.
Carbon, burned to carbonic acid	14,650	1.000	15.06
Carbon, burned to carbonic oxide	4,400	0.300	4.56
Carbonic oxide	4,400	0.306	4.56
Marsh gas, CH_4	23,513	1.617	24.34
Olefiant gas, C_2H_4	21,344	1.468	22.10
Hydrogen	62,500	4.270	64.80
Hydrogen, deducting latent heat of steam	53,800	3.670	55.70
Sulphur	4,030	0.275	4.14
Straw, with 16% water	5,200	0.355	5.38
Wood, kiln-dried	8,000	0.546	8.28
Wood, air-dried, 20% moisture	5,600	0.382	5.80
Peat, kiln-dried	10,000	0.683	10.35
Peat, air-dried, 20% moisture	6,500	0.443	6.73
Charcoal from wood, dry	13,000	0.888	13.46
Charcoal from peat, dry	11,600	0.792	12.01
Coal, lignite, air-dried	11,000	0.752	11.39
Coal, bituminous — good quality :			
from	13,000	0.888	13.46
to	15,700	1.070	16.25
average	14,100	0.964	14.60
Coal—anthracite :			
from	14,000	0.956	14.49
to	16,200	1.105	16.77
average	15,000	1.023	15.33
Coke :			
from	12,000	0.820	12.42
to	13,700	0.935	14.18
Block fuel (briquettes)	15,000	1.022	15.53
Petroleum :			
from	18,000	1.230	18.65
to	20,000	1.365	20.70
Natural gas (Pennsylvanian)	26,000	1.775	26.92

It will be seen that for every pound of carbon burned to CO instead of CO₂ there is a direct loss of 10,250 B.Th.U., but if this carbon monoxide is subsequently converted into carbonic acid there is no ultimate loss. One pound of carbon gives 2.33 pounds of CO, and $2.33 \times 4400 = 10,250$ B.Th.U. as the result of the combustion of the gases formed from the original pound of carbon.

From the figures given in Table V, the total heat of combustion of any fuel whose analysis is known can be determined, the formula being :—

$$14,650 C + 62,500 \left(H - \frac{O}{8} \right) + 4000 S,$$

where C , H , O and S , represent the actual weight of the various combustibles in one pound of fuel.

This figure is the gross calorific value, and assumes that all the water formed by the union of the hydrogen and oxygen is condensed and gives up its latent heat, and it is also assumed that the oxygen present is already in combination with its proportion of hydrogen. It is not known definitely whether these elements are in combination or not, and if not, heat will be developed by their union to exactly the same extent as if the oxygen were added in the air supply. In many cases the results of tests in the calorimeter give results agreeing more closely with the formula :—

$$\text{Total heat of combustion} = 14,650 C + 62,500 H + 4000 S.$$

The sulphur is usually present in very minute quantities, and the last item is therefore generally neglected.

In most actual cases in practice, the temperature of the gases leaving the furnace is considerably above the temperature at which the steam formed by the combustion of the hydrogen will condense to water, hence the latent heat of the steam will be carried away in the flue gases.

The latent heat of steam being 966 B.Th.U. and there being 9 pounds of steam formed by the combustion of 1 pound of hydrogen, the total heat units carried away as latent heat in the steam will be $966 \times 9 = 8694$, say 8700 B.Th.U. Hence the net gain from the combustion of the hydrogen will be $62,500 - 8700 = 53,800$ B.Th.U. per pound of hydrogen, and the formula becomes :

$$\text{Total heat} = 14,650 C + 53,800 \left(H - \frac{O}{8} \right) + 4000 S,$$

or alternatively, if the oxygen is free,

$$14,650 C + 53,800 H + 4000 S.$$

Table VI gives a comparison, for several fuels of various compositions, between the figures for the total heat of combustion obtained by experiment in a calorimeter and by calculation, both taking into account and neglecting the percentage of oxygen in the fuel, and it will be seen that, in the majority of cases, the result of assuming the oxygen to be free and uncombined with the hydrogen gives results that are closer to the experimental values.

TABLE VI

*Calculated and Experimental Calorific Values
of Fuel*

Composition of fuel, per cent.				Calorific values.		
				Experi- ment.	Calculated. H.	Calculated. $H-\frac{O}{8}$
C.	H.	O.	S.			
66.31	4.85	14.42		12,600	12,700	10,400
70.57	5.44	11.99		13,200	13,710	11,700
76.87	4.68	9.22		14,700	14,120	12,600
83.82	4.60	5.79		15,600	14,980	14,100
78.18	5.45	8.07	1.03	14,330	14,320	13,770
81.48	6.48	4.53	2.00	15,280	15,380	15,070
83.22	5.16	6.87	1.00	14,450	14,890	14,420
80.41	5.05	10.42	0.71	14,260	14,410	13,710
69.72	4.69	11.15	1.44	12,670	12,530	12,020

Having obtained the heat of combustion of the fuel in the manner indicated above, it is a simple matter to calculate the theoretical temperature obtained from a knowledge of the specific heat of the gases resulting from the chemical reactions.

The specific heat of the various substances and their densities are given in Table VII (see page 39).

Taking, for example, the combustion of 1 pound of carbon, it has been shown that 2.67 pounds of oxygen are required for complete combustion and this amount of oxygen requires the supply of 11.5 pounds of air. The weight of products must therefore be $1 + 11.5 = 12.5$ pounds, of which 8.83 pounds will be nitrogen, while the weight of CO_2 will be 3.67 pounds.

The specific heat, given in column 5 of Table VII, represents the number of B.Th.U. required to raise its temperature $1^\circ F$.

The amount of heat required to raise the pro-

ducts of combustion from 1 pound of carbon is therefore estimated as follows :—

3.67 pounds of carbon dioxide	$\times 0.2169$	$= 0.7953$
8.83 „ „ nitrogen	$\times 0.2438$	$= 2.1527$
		Total $= 2.9480$

The temperature by which the gases will be

TABLE VII

Substance.	Specific density air at 32° F. = 1.	Weight per cu. ft. in pounds.	Volume in cu. ft. per pound.	Specific heat of gas (at constant pressure)
Air—dry and pure —32° F.	1.0000	0.080728	12.387	} 0.2375
Air—dry and pure 62° F.	0.9426	0.076097	13.141	
Carbonic oxide (CO)	0.9678	0.078129	12.799	0.2450
Carbonic acid (CO ₂)	1.5290	0.123434	8.101	0.2169
Hydrogen	0.0693	0.005910	178.86	3.4090
Oxygen	1.10563	0.089255	11.204	0.2175
Nitrogen	0.97137	0.078417	12.752	0.2438
Sulphurous acid (SO ₂)	2.21126	0.178511	5.602	0.1554
Steam at 212° F.	0.47034	0.037970	26.337	0.4805
Marsh gas (CH ₄)	0.55900	0.045127	22.160	0.5930
Olefiant gas (C ₂ H ₄) (ethylene)	0.97840	0.078984	12.661	0.404
Coal gas (average quality)	0.455	0.036731	27.225	0.25
Ash				0.2

raised, assuming that there is no leakage of heat from the furnace, is therefore given by dividing the total heat of combustion by the number of heat units required to raise the temperature one degree. This may be expressed :—

$$T = \frac{C}{W \times S}$$

where C = calorific power or heat evolved by the union of 1 pound of the substance with oxygen.

W = Weight of products of combustion.

S = Specific heat of products of combustion.

In the present case the temperature rise will be :—

$$14,650 \div 2.9480 = 4969^{\circ} \text{ F.}$$

A similar calculation will give the theoretical temperature for any fuel. Taking, for example, a coal of the composition given in the first line of Table VI, which has, by calorimetric test, a calorific value of 12,600 B.Th.U. per pound, the theoretical temperature of combustion is obtained as follows :—

Weight of air required for complete combustion

$$\begin{aligned} &= 11.5 \times 0.6631 + 34.5 \left(0.0485 - \frac{0.1442}{8} \right) \\ &= 7.625 + 1.05 \\ &= 8.675 \text{ pounds.} \end{aligned}$$

Of this 1.995 pounds will be oxygen and 6.68 pounds nitrogen. The nitrogen content of the coal is not given, but may be taken as about 1.5 per cent., making the total amount of this constituent in the gases 6.695 pounds. The ash and sulphur may be neglected. The amount of CO_2 produced will be 2.4336 pounds, and of H_2O 0.4365 pound.

The amount of heat required to raise the products of combustion of 1 pound of the coal will therefore be :—

Carbonic acid . . .	$2.4336 \times 0.2169 = 0.5278$
Water . . .	$0.4365 \times 0.4805 = 0.2097$
Nitrogen . . .	$6.695 \times 0.2438 = 1.6322$
Total B.Th.U.	<u>2.3697</u>

The theoretical temperature rise obtained will therefore be :—

$$12,600 \div 2.3697 = 5317^{\circ} \text{ F.}$$

In actual practice there would be a considerable excess of air. Assuming this excess to be, say, 60 per cent., a usual figure, the rise of temperature will be considerably less than the maximum figure estimated above. The extra weight of air supplied will be 5.205 pounds, and the amount of heat required to raise the gases by one degree will be increased by $5.205 \times 0.2375 = 1.2362$ B.Th.U.

The theoretical temperature rise will now be :—

$$12,600 \div (2.3697 + 1.2362) = 3494^{\circ} \text{ F.}$$

The decrease of temperature, due to the excess of air, is therefore 1823° F.

It is, of course, impossible to obtain actual temperatures anywhere near these figures owing to the loss of heat by radiation and conduction through the furnace walls, etc., but the figures given above will show the importance, where high temperatures are required, of keeping the weight of air supplied down to the lowest possible figures compatible with complete combustion of the fuel.

Calculations based on the composition of the fuel as above give the theoretical rise of tem-

perature, and to obtain the actual temperature as shown by a thermometer the temperature of the air and fuel entering the furnace must be taken into account. Thus if air is supplied at 65° F., the recorded temperature, with 60 per cent. excess of air, will be increased to 3555° F.

As a rough approximation, it may be taken that with a good quality coal 12 pounds of air supplied per pound of fuel will result in a furnace temperature of about 5000° F., while with 18 pounds air per pound of fuel the temperature will be about 2700° F., and every additional pound of air will reduce the temperature by approximately 100° F.

With 30 pounds of air per pound of fuel, the furnace temperature will be below 1700° , and as at a temperature of 2700° a furnace will radiate over 100 per cent. more heat than when at a temperature of 1700° , there is a considerable loss in furnace efficiency, in addition to the loss of heat in the flue gases, which has been dealt with elsewhere.

The approximate temperature of a furnace can be readily estimated if the percentage of CO_2 in the flue gases and the calorific value of the fuel are known, from the following formula :—

$$T = \frac{C}{0.24 \left(\frac{19.2 \times 12}{\% \text{CO}_2} + 1 \right)}$$

where T = temperature in degrees Fahrenheit,

C = calorific value of fuel in B.Th.U. per pound.

In many cases, the air for combustion is preheated, resulting in a corresponding increase in the combustion temperature, and it may in some cases be found that the increase in efficiency is actually greater than is represented by the heat added to the air, owing probably to a reduction in the loss of heat from the furnace and an improvement in the efficiency of combustion.

Air-heaters for this purpose usually consist of nests of cast-iron pipes, of rectangular or round section, or of narrow cells constructed of steel plate and placed in the flues in such a way that the air for combustion is drawn through the pipes or cells, while the hot gases pass between them.

The rate of transmission of heat from the flue gases to the air varies with the temperature difference and with the velocity of the air. The number of B.Th.U. transmitted per square foot of heating surface per hour per degree difference of temperature between flue gases and air varies from 1.8 for an air velocity of 1000 feet per minute to 2.75 at 1900 feet per minute and 3.3 for 2500 feet per minute. It is found that there is very little, if any, difference between the rates of transmission for cast iron and steel, the main point being to divide up the air and gases into thin streams so that as large a surface as possible is provided for the passage of heat.

It is found that the amount of unburnt carbon in the ashes is decidedly less when preheated air is used, and the length of flame is also reduced owing to the high temperature and more rapid and complete combustion.

In the case of steel furnaces, glass tanks and similar plants, the preheating of the air is effected by means of brick chequer-work. The hot gases are passed through one section of the chequer-work, which is thus raised to a high temperature, while the incoming air is passing through the other section. After a sufficient time has elapsed to enable the brickwork to be thoroughly heated, the air current is changed over by means of a reversing valve, so that the air now passes through the section which has just been heated while the hot gases are passed through the other part of the regenerator.

In the case of some gas retort settings and similar installations, the air and gas passages are separated by thin tiles or bricks of refractory material. The heat passes through the dividing walls, and the action is continuous, no reversing valve being needed.

The use of these regenerators or recuperators has been general for many years in furnace practice, but the adoption of similar principles for boiler works has only recently become at all general, although Howden adopted the idea many years ago by drawing the air for combustion through channels formed in the boiler uptake.

CHAPTER III

FUELS

ALL fuels in common use consist mainly of carbon and hydrogen, with small proportions of oxygen, sulphur and various impurities, and may be divided into three main divisions, viz., solid, liquid and gaseous.

Solid fuels comprise coal, coke, wood, peat, charcoal and block fuel or briquettes.

Liquid fuels comprise oils of various kinds.

Gaseous fuels comprise natural gas, coal gas, producer gas, water gas, coke oven and blast furnace gases and oil gas.

Solid fuels are in most general use and the majority of furnaces are designed for their combustion. They burn moderately slowly and the mass of glowing fuel in the furnace forms a reservoir of heat which assists in maintaining the process of combustion.

If the lumps are large they present a small surface only to the air and combustion is very slow, while if they are extremely small the air cannot penetrate the mass of fuel, unless it is supplied under pressure, and combustion will again be very slow. If, however, such extremely fine solid fuel is projected into the furnace in such a way that the particles are surrounded by air at a high temperature, the surface presented to the oxygen is very large and combustion takes place extremely rapidly.

Liquid fuels do not burn readily in bulk, owing to the small surface exposed to the air, and they are

in practice injected into the furnace through a suitable nozzle or burner in a finely atomised spray by means of a steam or air jet. In this way they burn readily with the production of a very high temperature.

Gaseous fuels burn very readily, as the molecules are not held together with any great force and the gas commences to diffuse as soon as it leaves the burner. Hence the molecules freely combine with the oxygen of the air, and with proper proportions of gas and air combustion is very complete.

Gaseous fuels now play a considerable part in industrial furnace practice, as the temperatures may be easily controlled within the limits required for any particular process, while any necessary type of flame can be produced.

The various types of fuels will now be considered in detail.

Wood.—Wood is the hardened tissue of trees and consists mainly of cellulose, a substance having the chemical composition of $C_6H_{10}O$. This substance contains 44.42 per cent. carbon, 6.22 per cent. hydrogen and 49.36 per cent. oxygen by weight, and the composition is the same for all classes of wood. As the tree grows, various materials, mainly consisting of carbon and hydrogen, are deposited in the cells of the tissue, so that the average wood contains more carbon than is shown in the composition of cellulose, together with a certain amount of free hydrogen and a considerable proportion of water derived from the sap.

The following figures (Table VIII) are given by Sexton and Davidson for the composition of various woods.

TABLE VIII.

1.	2.	3.	4.	5.	6.
	Oak 120 years dry.	Birch 60 years dry.	Willow dry.	Average dry.	Air dried.
Carbon .	50.97	50.59	51.75	51	40.0
Hydrogen .	6.02	6.21	6.19	6	4.8
Oxygen .	41.96	42.16	41.06	42	32.8
Nitrogen .	1.27	1.01	0.98	1	0.8
Ash .	1.93	2.10	3.67	2	1.6
Moisture .	—	—	—	—	20.0

In columns 2, 3, 4 and 5 the percentages of C, H, O and N are calculated on an ash-free basis. The ash consists mainly of carbonates of potassium and calcium. Freshly-felled timber contains about 50 per cent. of moisture, depending on the kind of wood, age and season of felling, but after a few weeks' exposure to air, under cover, the moisture is reduced to about 20 per cent., while by further drying in a suitable kiln the moisture content may be reduced to 10 per cent. or less.

The calorific value of moisture-free wood is about 7000 B.Th.U. per pound, and if air dried only, about 5600 B.Th.U., and all wood has approximately the same value. There is only a difference of about 8 per cent. between the various kinds of timber and only 3 or 4 per cent. between the values of the woods most commonly used as fuel.

From the figures given above it will be seen that about $2\frac{1}{2}$ pounds of wood are equivalent in heating value to 1 pound of good average coal.

Owing to its light cellular nature wood burns very easily and is not of great value as a fuel except in those countries where it is very abundant and coal is scarce, or where a considerable amount of wood refuse is made during manufacturing operations. In this case it can either be burned under boilers or used in a producer for gas generation.

Straw.—Straw is occasionally used as a fuel where it is plentiful and other fuels are scarce. It has a calorific value when dry of about 6300 B.Th.U. per pound, or in its natural state, after deducting the latent heat of the steam produced from the moisture content, about 5150 B.Th.U. per pound.

Straw has an average composition as given in Table IX :—

TABLE IX.

Carbon	36 per cent.
Hydrogen	5 „
Oxygen	38 „
Nitrogen	0.45 „
Ash	4.75 „
Moisture	15.8 „

Other varieties of vegetable refuse, such as spent tan, may be used when available in sufficient quantity, but the heating value is low, and special types of furnace are required for burning these fuels satisfactorily.

Megass.—In cane-sugar producing districts large quantities of vegetable refuse are available in the shape of the cane from which the juice has been extracted. This is known as megass, or bagasse, and usually contains from 10 to 12 per cent. of

fibrous material, which is mainly carbon, a considerable quantity of moisture and a small proportion of sugar and molasses which have not been extracted in the mill processes.

The calorific value of dry megass is about 8300 B.Th.U. per pound, but the actual value of the material, as fired, will be considerably less than this figure on account of the heat absorbed in evaporating the moisture content.

Assuming that the megass has a moisture content of 50 per cent., the actual calorific value of the material will be about 3600 B.Th.U. per pound.

Special types of furnace have been designed for burning megass, the steam supply of the mills being generated entirely from the waste material, usually in water tube boilers.

Peat.—Peat, which occurs in large masses in certain countries, consists of decayed vegetable matter, and is usually found in low-lying and moist districts. It may be considered as the first step in the formation of coal, but is of different composition from both wood and coal and is frequently contaminated by appreciable quantities of mineral compounds.

The composition of peat varies very considerably in different districts, and when first cut may contain up to 80 per cent. of moisture.

The blocks of peat are usually stacked in long rows in the open in order to get rid of as much of the moisture as possible, and after thorough drying the moisture is reduced to 20 or 25 per cent.

The composition of dry peat, as given by Percy, is shown in Table X.

TABLE X.

Carbon	from	54.02	per cent.	to	61.04	per cent.
Hydrogen	„	5.21	„	„	6.83	„
Oxygen	„	28.18	„	„	32.23	„
Nitrogen	„	1.42	„	„	2.30	„
Ash	„	1.83	„	„	9.73	„

The upper layers are light in colour and density, while the lowest portion, which is much older and more thoroughly decayed, is nearly black and of much greater density. Peat weighs, on an average, about 30 pounds per cubic foot. It is generally used for domestic purposes, though plants have been installed for carbonising peat in retorts in order to obtain gas, coke and other products.

Coal.—Coal and its derivatives form the most important body of fuels and are in almost universal use except where oil or natural gas can be employed economically.

Coal is made up almost entirely of vegetable matter, and was formed by the growth and decay of primeval forests, which were in the course of time submerged and had deposited over them masses of mud and sand which subsequently hardened into shale and sandstone. In most cases, this process was repeated several times, giving rise to the various seams which are found in many coal mines.

Coal varies greatly in its nature and composition, ranging from brown coal or lignite, which is intermediate between wood and true coal, through the

various grades of bituminous coal to anthracite. Cannel coal, which was probably formed from vegetable matter collecting at the bottom of lakes or pools into which it had been brought by streams, often contains a considerable amount of clay and shale.

Lignite, or brown coal, is widely distributed throughout Europe, but is only found in England in one district. It burns easily, with a long, smoky flame, but is not very rich in carbon, and some lignites contain large quantities of moisture and are not very far removed from hard peat.

According to Sexton and Davidson, the average composition of dry lignite is as given in Table XI.

TABLE XI.

Average Composition of Lignite.

Carbon	.	.	.	68	per cent.
Hydrogen	.	.	.	5.5	"
Oxygen	.	.	.	26.5	"
Ash	.	.	.	2.0	"

Lignite is not in great use for commercial purposes, except in districts where better fuels are not available.

Bituminous Coals. — Bituminous coals contain a considerable proportion of volatile matter and burn with a yellow, smoky flame. They vary very greatly in composition and in the nature of the coke formed on distillation of the coal in a closed retort.

If some coals be distilled in this way, although they may be in a fine state of division when

charged into the retort, they form a dense, compact mass of coke. These are known as caking coals. Other coals, if treated in a similar way, only produce a soft, friable coke, of little use for metallurgical purposes. These are known as non-caking coals.

In the case of some coals of poor caking quality, the coke is greatly improved if the coal is compressed, before distillation, into a solid block, and this process is largely used in the manufacture of furnace coke for iron and steel smelting and similar purposes.

Bituminous coal is generally black in colour, though in some districts dark brown varieties are found. The caking property appears to depend largely on the relative proportions of carbon and oxygen, as both those coals which approach lignite and those which are more nearly allied to anthracite do not cake, whereas the intermediate grades possess this property.

Bituminous coals ignite readily and burn easily without requiring the strong draught necessary for burning anthracite. The non-caking coal burns more readily, as the heat does not cause the lumps to become pasty and run together, while the caking coals, being rich in the volatile hydrocarbons, are particularly useful for gas-making.

The general properties of the various classes of bituminous coals, as stated by Sexton and Davidson, are given in Table XII.

Non-Caking Coals.—The long flame non-caking coals yield large quantities of gas and tarry matters,

TABLE XII

	Composition.			Products of distillation.				Nature of coke.
	Carbon per cent.	Hydrogen per cent.	Oxygen per cent.	Ammonia, per cent.	Crude tar per cent.	Gas per cent.	Coke per cent.	
Non-caking coal, long flame.	75 to 80	5.5 to 4.5	19.5 to 15.0	12 to 5	18 to 15	20 to 30	50 to 60	Slightly coherent.
Gas coal.	80 to 85	5.8 to 5.0	14.2 to 10.0	5 to 3	15 to 12	20 to 17	60 to 68	Caked but soft many crevices.
Furnace coal.	85 to 89	5.0 to 5.5	11.0 to 5.3	3 to 1	13 to 10	16 to 15	68 to 74	Caked, moderately compact.
Coking coal.	88 to 91	5.5 to 4.5	6.0 to 5.5	1	10 to 5	15 to 12	74 to 82	Caked hard and compact.
Steam coal, smokeless.	90 to 93	4.5 to 4	5.5 to 3	1 to 0	5 to 2	12 to 8	82 to 90	Slightly coherent.

but the calorific power is not very high. They include the majority of hard splint coals used for blast furnaces in Scotland and Staffordshire.

The approximate analysis of these coals is given below :—

TABLE XIII

Composition of Non-caking Bituminous Coals

(Roscoe and Schorlemmer.)

Locality.	C.	H.	O.	N.	S.	Ash.
South Staffordshire.	78.57	5.29	12.88	1.84	0.39	1.03
" "	71.13	5.01	9.67	1.58	0.81	1.35
St. Helens, Lancs. .	75.81	5.22	11.14	1.93	0.90	5.00
Dowlais, South Wales	89.33	4.43	3.25	1.24	0.55	1.20
" "	87.62	4.34	2.52	1.13	1.07	3.32
" "	82.60	4.28	3.44	1.28	1.22	7.18
Scotland	76.08	5.31	13.33	2.09	1.23	1.96
" "	80.63	5.16	10.61	1.33	0.84	1.43
Blanzy, France . .	76.48	5.23	16.01	—	—	2.28
Pas de Calais, France	82.68	4.18	4.54	—	—	8.60
Hungary	73.38	3.86	11.65	—	0.58	10.53
Aix-la-Chapelle .	91.45	4.18	2.12	—	—	2.25

Gas Coals.—These coals have a slightly greater density than those in the foregoing class, the specific gravity being about 1.3. They are hard and dense, but the coke formed on distillation, though very suitable for domestic use and for the production of producer gas and water gas, is not sufficiently hard for blast furnace use.

These coals burn with a long, luminous flame and are suitable for use in reverberatory furnaces. Some of the harder varieties, found in Scotland, are used for blast furnaces.

Furnace coals are also used for gas-making and for reverberatory furnaces, and are very largely

used for domestic purposes. They burn with a bright, luminous flame and on heating swell up and form a dense grey coke.

In Table XIV will be found the composition, as given by Roscoe and Schorlemmer, of various caking coals :—

TABLE XIV

Composition of Caking Bituminous Coals

Locality.*	C.	H.	O.	N.	S.	Ash.
Northumberland .	78.65	4.65	13.66	—	0.55	2.49
„ .	82.42	4.82	11.11	—	0.86	0.79
„ .	81.41	5.83	7.90	2.05	0.74	2.07
„ .	78.69	6.00	10.07	2.37	1.51	1.36
Nottinghamshire .	77.40	4.96	7.77	1.55	0.92	3.90
Blaina, South Wales	82.56	5.36	8.22	1.65	0.75	1.46
„ „	83.44	5.71	5.93	1.66	0.81	2.45
„ „	83.00	6.18	4.58	1.49	0.75	4.00
Epinal .	81.12	5.10	11.25	—	—	2.53
Charleroi .	86.47	4.68	5.30	—	—	3.55
Pas de Calais .	86.78	4.98	5.84	—	—	2.40
Hungary .	86.93	4.35	6.47	—	0.86	0.89

Coking coals are similar to furnace coals, but harder, and on distillation they give a hard, compact coke which is suitable for use in blast furnaces, as it will withstand a considerable weight without crushing. They do not give off so much gas as the softer grades and burn with a shorter flame. They are in considerable use for domestic and steam-raising purposes, as well as for the manufacture of furnace coke.

Cannel Coals.—As mentioned above, cannel coals are formed in a somewhat different manner from ordinary coals. They are dull in colour and somewhat similar to shale in appearance. They

burn with a very long, luminous and smoky flame and when distilled yield a large volume of rich gas, also, when carbonised at a comparatively low temperature, a considerable quantity of tar oils.

The composition of typical British cannel coals is given in Table XV :—

TABLE XV
Composition of Cannel Coals
(Roscoe and Schorlemmer.)

Locality.	C.	H.	O.	N.	S.	Ash.
Wigan	84.07	5.71	7.82	—	—	2.40
„	80.07	5.53	8.08	2.12	1.50	2.70
Ashton-under-Lyne.	83.25	5.75	5.06	—	0.86	3.48
Tyneside	78.06	5.80	3.12	1.85	2.22	8.94
Mold, Wales	79.87	5.78	8.09	—	0.57	2.85
„ „	77.81	8.47	6.32	—	0.71	6.01
Scotland	66.44	7.54	10.84	1.36	0.84	12.98
„	63.10	8.91	7.25	—	0.96	19.78

Anthracite Coals.—These are the so-called smokeless steam coals and are intermediate in character between the furnace and coking coals and true anthracite. They are hard and dense, with a specific gravity of 1.35 to 1.4, are somewhat difficult to ignite, and burn with the evolution of little flame and smoke. They require a fairly strong draught for satisfactory combustion. When distilled, they give off little gas but a large proportion of coke, which is of a powdery nature and of little use.

The composition varies from 90 to 93 per cent.

carbon, 4 to 4.5 per cent. hydrogen and 3 to 5.5 per cent. oxygen.

Anthracite.—True anthracite is extremely hard and brittle, ignites with difficulty and burns with an intense heat but without smoke or flame. The specific gravity is 1.5 to 1.6. It contains very little volatile matter and on distillation leaves a residue of 96 to 98 per cent. by weight.

Anthracite is used for furnace purposes, and for domestic use in closed stoves, in which it burns very slowly.

The composition of various South Wales and Pennsylvania anthracites is given in Table XVI (Roscoe and Schorlemmer):—

TABLE XVI

Composition of Anthracites

Locality.	C.	H.	O.	N.	S.	Ash.
South Wales . . .	92.56	3.33	2.53	—	—	1.58
„ „ . . .	90.39	3.28	2.98	0.83	0.91	1.61
„ „ . . .	87.02	3.14	2.16	0.90	0.67	6.11
Pennsylvania . . .	90.45	2.43	2.45	—	—	4.67
„ . . .	92.59	2.63	1.61	0.92	—	2.25
„ . . .	84.98	2.45	1.15	1.22	—	10.20

It is generally considered that peat, lignite and bituminous coal form the intermediate stages in the transformation of wood and vegetable fibre into anthracite, due to gradual decomposition and the evolution of the volatile constituents of the original matter. The gradual conversion of woody fibre into coal and anthracite is illustrated by the following table, given by Dr. Percy:—

TABLE XVII

		Carbon.	Hydrogen.	Oxygen.
Wood	. . . .	100	12.18	88.07
Peat	. . . .	100	9.85	55.67
Lignite	. . . .	100	8.37	42.42
Bituminous coal	. . . .	100	6.12	21.23
Anthracite (Wales)	. . . .	100	4.75	5.28
Anthracite (Pennsylvania)	. . . .	100	2.84	1.74

All coals contain small amounts of foreign matter, as well as moisture, which in the ordinary condition of coal as supplied may be from 2 to 5 per cent.

Sulphur is generally present in amounts varying from 0.3 to 5 per cent., but although it has some heating value, the amount present is generally so small as to be negligible. The effect of the sulphur is, however, important in cases where the gases have to be handled at a temperature below that at which the moisture content will condense, as the action of the acid then formed on steel work is very rapid.

Chlorine is also present in small quantities in many coals, but is only important from the action it may have on any brass or copper with which it may come in contact or on the brickwork in the case of coal used for coking purposes. Nitrogen is always found in coal in proportions varying from 1.5 to 0.7 per cent., and traces of other elements may also be present.

All coals on combustion leave a residue of ash, which is more or less fusible at ordinary furnace temperatures. The quantity of ash is important, together with its fusibility, as trouble occurs in

many furnaces owing to the clogging up of the firebars by fusible ash or slag. The slag hardens on reaching the comparatively cool bars, and may seriously reduce the efficiency of the furnace by closing up the air spaces. In furnaces burning powdered fuel special precautions have to be taken to prevent trouble from the accumulation of slag.

The quantity of ash is also important, as it takes away a certain amount of heat from the furnace. The specific heat of ash is about 0.2 and as it generally leaves the furnace at a high temperature the quantity of heat lost may be appreciable. In the case of gas producers constructed with a water bottom, this loss is not so important, as a certain amount of steam is generated by the heat of the ash, and this steam takes part in the reactions in the producer.

When coal is exposed to the atmosphere for a considerable period, partial oxidation may take place, resulting in a reduction of the calorific power of the fuel. Under certain conditions, this process may go on sufficiently rapidly to cause ignition of the mass of coal. On this account it is usual, where large quantities of coal are kept in store for a long period, to make provision for taking the temperature of the mass of coal from time to time, so that any undue rise of temperature may be noticed and the heated coal removed. In some cases coal is stored under water to prevent this oxidation.

Charcoal.—This fuel was at one time in considerable use for iron smelting and other industrial purposes, but is now only used to a very limited

extent, and in districts where other fuels are difficult to obtain.

Charcoal is produced by the distillation of wood in the absence of air, and has an approximate composition of carbon 95, hydrogen 0.5, oxygen 1.5 and ash 3.0.

Coke.—Coke, produced from coal by distillation in closed retorts constructed of fireclay or refractory brick and heated externally, forms one of the most important fuels in modern industry, and may be used directly in its solid state, or indirectly after conversion to gas in a producer or generator.

The old method of manufacturing coke in Beehive ovens is now very little used and the principal sources of coke are gas works, where it may be produced in horizontal, inclined or vertical retorts of various types and sizes, and the large horizontal chamber ovens now in general use at collieries for manufacturing metallurgical coke.

Gas works coke varies considerably in its nature, according to the type of retort in which it has been made and the quality of coal used for its production. It is especially suitable for domestic use, for the production of water gas and for those industrial furnaces where a particularly hard and strong fuel is not required.

Coke produced in the usual horizontal ovens is hard and dense and is used mainly in blast furnaces, where it has to withstand a heavy load without crushing. It has a density of about 0.9 and a crushing strength of 500 to 1500 pounds per square inch.

The calorific power of coke is approximately the

same as that of the coal from which it has been manufactured.

Coke requires a strong draught for its proper combustion and is somewhat difficult to ignite. It burns with evolution of intense heat, but without flame, and for domestic purposes is generally used in closed stoves.

A form of coke, produced by partially carbonising coal at a comparatively low temperature (about 800° F.) until about 90 per cent. of the volatile constituents have been driven off has been introduced. This fuel will ignite easily and will burn in an open grate without smoke. Although this fuel is being produced commercially it has not come into very extensive use.

The composition of coke naturally varies with that of the coal from which it is produced, the composition of three typical samples being given by Sexton and Davidson, as follows :—

TABLE XVIII

Carbon	. 85.84 per cent.	93.15 per cent.	84.92 per cent.
Hydrogen	0.52 „	0.72 „	4.53 „
Oxygen	1.38 „	0.90 „	6.66 „
Nitrogen	0.86 „	1.28 „	0.65 „
Ash	. 11.40 „	3.95 „	2.28 „

In modern coking plants the coal is generally disintegrated and washed before carbonisation, in order to reduce, as far as possible, the proportion of ash-forming materials, such as stone and shale, known generally as “dirt,” while in many cases, especially where a coal of poor caking properties is

used, the coal is compressed by a stamping machine before it is fed into the ovens.

As mentioned above, the calorific power of coke is practically the same per pound as that of the original coal, but as the weight of the coke is considerably less, the total amount of heat produced by its combustion is correspondingly less. A large amount of heat is required to effect the distillation of the volatile constituents of the coal, and this heat is to a great extent lost, in spite of the use of part of the gases for heating the ovens.

Coke requires a strong draught for its combustion and is particularly useful where material is to be heated by contact or radiation, and where smokeless combustion is required.

Patent Fuel or Briquettes.—In South Wales and some other districts large quantities of patent fuels are produced from the accumulation of fine coal which is too small to be of any real value otherwise. This material is broken into a coarse powder, dried and pressed into blocks or briquettes with the aid of pitch or some other material as a binder. The calorific power is approximately the same as that of the coal from which they are produced and may be taken as about 14,000 B.Th.U. per pound.

Small anthracite briquettes, or “Ovoids,” are used for domestic purposes in closed stoves, and in France and other countries large quantities of blocks are used for locomotive firing.

CHAPTER IV

LIQUID FUELS

THE liquid fuels in general use comprise natural oils or petroleum, shale oil and oils prepared from tar and similar materials, while for internal combustion engines large quantities of petrol, benzol, and alcohol are used.

Natural oil is found in many parts of the world, but the principal supplies are derived from the United States, Mexico, Roumania and Galicia, Russia, Peru, Persia and Iraq, Burma and the Dutch East Indies. Oil has also been found in Great Britain, but not so far in very large quantities. The composition varies greatly with the district from which the oil is obtained.

The oil is obtained by means of bore-holes or wells from which it is pumped, though when the oil-bearing strata are first tapped, the oil is frequently under sufficient pressure to cause it to flow naturally from the bore-hole.

The crude oil is distilled in iron retorts and the temperature gradually raised, the products distilling off at different temperatures being collected separately as light and heavy spirits or naphthas and light and heavy oils. The lighter products may be used for internal combustion engines or other commercial uses, while the heavier oils are used as fuels and for the production of lubricating oils. Engines are also built suitable for using these classes of oils.

Table XIX gives the approximate composition of a large number of typical oil fuels, with the

TABLE XIX

Composition of Oil Fuels and Air Required for Combustion

Description of oil.	Composition.		S.	B.Th.U. per pound.	Specific gravity.	Weight of air per pound.	Volume of air per pound.
	C.	H.	O.				
Admiralty fuel oil . . .	86.4	11.55	1.71	0.34	17,930	0.928	13.94
Black oil . . .	86.44	11.83	1.22	0.51	17,959	0.928	14.01
Oil used, destroyer trials . . .	85.28	11.93	2.24	0.55	17,975	0.921	13.87
Petroleum refuse (Russian) . . .	87.1	11.7	1.2		22,700	0.928	14.03
Ordinary fuel oil . . .	86.2	12.57	0.92	0.31	18,175	0.888	14.25
Scotch shale oil (A) . . .	86.16	12.37	1.21	0.26	18,248	0.855	14.16
Scotch shale oil (B) . . .	85.35	12.44	1.92	0.29	18,317	0.862	14.06
Scotch blast furnace oil . . .	83.64	10.59	5.77		18,260	0.92	13.05
American "residuum" . . .	86.44	11.23	2.03	0.30	18,117	0.943	13.34
Russian astatki . . .	84.94	13.96	1.1		18,600	0.906	14.56
Diesel fuel oil . . .				0.45	17,921	0.923	
Diesel fuel oil, semi-refined . . .	85.05	12.15	2.43	0.37	17,996	0.904	13.91
							182.8

Description of oil.	C.	Composition.		S.	B.Th.U. per pound.	Specific gravity.	Weight of air per pound.	Volume of air per pound.
		H.	O.					
Refined petroleum (Russian).	86	14			21,070	0.825	14.75	193.8
Refined petroleum (American)	85.5	14.2	0.3		21,180	0.797	14.75	193.8
Double refined (American)	80.58	15.1	4.32		20,720		14.32	188.2
Light crude (Caucasian)	86.3	13.6	0.1		20,950	0.884	14.64	192.4
Heavy crude (Caucasian)	86.6	12.3	1.1		20,110	0.938	14.19	186.5
Heavy crude (Pennsylvanian)	84.9	13.7	1.0		20,880	0.886	14.48	190.3
Crude oil (Roumanian)	83.77	12.98	2.96	0.29	18,022	0.83	14.02	184.3
Solar oil (Texas)	85.35	12.92	1.56	0.17	18,344	0.862	14.24	187.2
Heavy crude (California)	84.4	11.1	3.91	0.59	18,800	0.95	13.42	176.3
Crude oil (Borneo)	87.8	10.78			18,800	0.96	13.84	181.9
Crude oil (Burmah)	86.4	12.1			18,800	0.85	14.14	185.8
Crude oil (Mexico)	82.7	11.0	2.95	3.35	19,000	0.942	13.30	174.9
Coal tar oil (gas works)	86.16	9.05	4.49	0.3	16,960	0.958	12.87	169.2
Crude coal tar oil (gas works)	82.0	7.6	10.4		15,810	1.05	11.63	152.9
Gas oil	83.72	7.29	8.17	0.82	15,977	1.044	11.84	155.7
Solid residuum (America)	97.85	0.49	1.19	0.47	14,420		11.41	150.0

calorific value and amount of air required for combustion.

Shale oil is produced in large quantities in Scotland by the distillation of shale in vertical retorts. A certain amount of steam is admitted during the process, and the products on condensation yield crude oil, light oil, naphtha and permanent gases, which may also be used as fuel, after the extraction of ammonia and light oils.

Tar oils are produced from the waste gases of coal-fired blast furnaces, coke ovens and gas works retorts.

Petrol is produced from natural oil or gas, and consists of the lighter portion of the distillates in the case of oil or of the heavier vapours in the case of natural gas. The specific gravity of petrol varies between 0.68 and 0.72 with a composition of approximately carbon 85 per cent. and hydrogen 15 per cent. The calorific value (gross) is about 20,000 B.Th.U. per pound.

Benzol is obtained mainly from coal tar produced in gas works and coke oven plants, but is also obtained from some natural oils. Its specific gravity is 0.87 to 0.88 and the gross calorific value about 17,800 B.Th.U. per pound. It requires more air for its combustion than petrol.

Alcohol (C_2H_5OH) is produced artificially from vegetable material, such as potatoes, beet, wood and peat. The specific gravity is 0.82, and the calorific value of 90 per cent. alcohol is 11,100 B.Th.U. per pound gross. It has a higher flash-point than either benzol or petrol and may there-

fore be more safely stored, while higher compression pressures may be used in the engine cylinder without danger of pre-ignition. The rate of explosion is slower than in the case of either of the other fuels, consequently the initial pressure on explosion does not reach so high a figure, but the average pressure is maintained and high thermal efficiency may be obtained by the use of high compression.

Table XX. gives the principal characteristics of petrol, benzol and alcohol.

TABLE XX

	Petrol.	Benzol.	Alcohol.
Specific gravity .	0.72	0.88	0.82
Boiling points .	140-340° F.	175-255° F.	175-230° F.
Calorific value per pound (gross B.Th.U.) . . .	20,100	17,800	11,100
Calorific value per pound (nett B.Th.U.) . . .	18,500	17,100	10,100
Air required for combustion per pound . . .	20	17.75	10.45
Safe limit of compression (pounds per square inch).	70	80	200
Heat of evaporation (B.Th.U.) .	337	368	940
Specific heat .	0.46	0.42	0.46

} 90%

Heavy oil engines, such as the Diesel and Semi-Diesel types, use a medium grade of oil, heavier than that used for the ordinary type of I.C. engine, but lighter than those generally used for furnace combustion. Paraffin is largely used for some classes of small engines.

Fuel oils should be practically free from water

and from grit, though the latter is partially due to free carbon, which is generally present to a greater or less extent. Sulphur should not be present to an amount exceeding 3 per cent., and for ordinary use the flash-point should be not less than 140° F.

Gaseous Fuels.—The combustible gases used as fuels are mainly produced from coal and coke, though oil is also used for gas generation, and in a few districts large accumulations of natural gas are found. This gas is mainly found in oil-bearing areas, but it is also met with in some coal districts.

Natural gas consists mainly of marsh gas or methane (CH_4) and hydrogen, with small quantities of other hydrocarbons, oxygen, carbon monoxide and dioxide. The calorific value is about 22,000 B.Th.U. per pound. This gas has been largely used in some parts of the United States, where the supplies are abundant and escape from the bore-holes at a considerable pressure.

The fuel gases produced from coal are : (1) coal gas proper, as produced in gas works, (2) coke oven gas, (3) blast furnace gas and (4) producer gas.

Coal Gas.—This gas is produced by the distillation of coal in closed retorts constructed of refractory blocks or sections. It is mainly used for domestic purposes, but large quantities are used in the smaller types of industrial furnaces, particularly where a sulphur-free gas is required, as in the ordinary course of manufacture almost the whole of the sulphur compounds are removed by purification with lime or oxide of iron.

Gas is now sold on the basis of its heating value, the unit being the therm, which represents 100,000 B.Th.U. gross. The average thermal value of town's gas is now usually 450 to 500 B.Th.U. per cubic foot. At the latter value 1 therm = 200 cu. ft.

In the past, when domestic illumination was mainly effected by means of flat flame burners, the gas contained a considerable proportion of hydrocarbons, which gave the flame its characteristic yellow colour, but now that incandescent burners are almost universally used, the illuminating power of the gas is not important, and in many towns the gas is largely diluted with water gas produced from the coke remaining in the retorts after the gas has been distilled off.

An average composition of coal gas is given in Table XXI. By calculation in the usual way this gas would have a calorific value of about 497 B.Th.U. per cubic foot.

TABLE XXI

Composition of Average Coal Gas

Methane (CH_4)	.	.	.	25.5 per cent.
Hydrogen (H)	.	.	.	46.0 ..
Nitrogen (N)	.	.	.	14.0 ..
Carbon dioxide (CO_2)	.	.	.	2.5 ..
Carbon monoxide (CO)	.	.	.	8.0 ..
Oxygen (O)	.	.	.	1.0 ..
Heavy hydrocarbons (C_mH_n)	.	.	.	3.0 ..

The calorific value of the hydrocarbons (C_mH_n) may be taken as about 2320 B.Th.U. per cubic

foot. The values for the other constituents have already been given.

The specific density of coal gas varies from 0·4 to 0·55, according to the composition and the extent to which it is diluted with other gases.

Coke Oven Gas.—This gas is also produced by the distillation of coal in closed chambers and is of somewhat similar composition to coal gas. The calorific value is about 400 to 500 B.Th.U. per cubic foot and the specific density from 0·35 to 0·5.

A large proportion of the gas produced in the distillation of the coal is used in heating the ovens, but considerable quantities are available for the production of power by combustion in gas engines or by burning in steam boilers. The volume of gas produced is about 8500 cubic feet per ton of coal, of which about 65 per cent. is required for heating the ovens.

In some cases, where there are coke ovens in convenient proximity, gas is taken in bulk by the local gas works, and either mixed with the ordinary coal gas or distributed alone for domestic use.

The composition of gas from Kopper's coke ovens, using Welsh coal, is as follows :—

TABLE XXII

Hydrogen	63·5 per cent.
Methane	23·1 „
Carbonic oxide	5·2 „
Carbonic acid	2·0 „
Oxygen	0·4 „
Ethylene	0·8 „
Nitrogen	5·0 „

Blast Furnace Gas.—Large quantities of combustible gas are given off during the production of iron in blast furnaces and a considerable proportion is available, and used, for the production of power. The gas contains a large amount of dust which must be reduced to a small proportion before the gas will burn satisfactorily, while for use in gas engines this dust content must be further reduced to avoid scoring in the cylinder and other engine troubles.

Blast furnace gas has a calorific value of about 90 to 110 B.Th.U. per cubic foot and a specific density of 1·1 to 1·2 as compared with air. This gas contains about 30 per cent. carbon monoxide, hydrogen and hydrocarbons. The actual composition varies according to the class of fuel used.

The volume of gas produced is about 160,000 cubic feet per ton of coke consumed, of which about 45 per cent. is required in the hot blast stoves.

The composition of various typical blast furnace gases is given in Table XXIIA :—

TABLE XXIIA

Composition of Blast Furnace Gases (Robinson)

	Scotch. (Wishaw).	Middlesbro'. and Coke.	Cleveland Coke.	Froding- ham. Durham Coke.	Brymbo.	West- phalia.
Carbonic acid .	7·21	15 to 20	12·4	6·3	5·7	7·8
Carbonic oxide .	25·83	24 to 20	27·1	26·9	34·0	30·7
Hydrogen .	4·55	1·5	1·3	2·4	1·3	3·3
Methane .	3·45	—	—	—	—	0·5
Nitrogen .	58·96	About 60	59·2	64·4	59·0	57·7
Combustible gases .	33·83	25·5 to 21·5	28·4	29·3	35·3	34·5

Producer Gas.—Producer gas is generated by blowing air through red-hot carbon, usually in the form of coke. By this means a combustible gas is formed containing about 34·7 per cent. of carbon monoxide. In modern types of producer coal is generally used in place of coke and a supply of steam is also admitted. This results in the formation of a richer gas owing to the decomposition of the water and the presence in the gas of the volatile constituents of the coal.

There are a large number of different types of producer now in use, such as the Siemens, Dowson, Mond, Wilson and Duff producers, which differ considerably in detail.

One of the best known is the Mond producer, manufactured by the Power Gas Corporation. The composition of a typical Mond gas, made from bituminous coal, is given in Table XXIII.

TABLE XXIII

Composition of Mond Gas from Bituminous Coal

	Vol. per cent.	
Carbonic oxide (CO)	. 23	
Hydrogen (H)	. 17	
Marsh gas (CH ₄)	. 3	
Carbonic acid (CO ₂)	. 5	
Nitrogen and moisture	. 52	
Total combustibles	. 43	
Calorific value—gross	. 169·2	B.Th.U. per pound.
„ „ —nett	. 157·5	„ „ „

One ton of ordinary slack coal will yield, in a Mond producer, about 140,000 to 150,000 cubic feet of gas of a calorific value of 160 B.Th.U. per

cubic foot. About $2\frac{1}{2}$ tons of steam are blown in for each ton of fuel.

The specific density of producer gas varies from 0.78 to 0.82.

A considerable amount of heat is lost in the producer, amounting to 15 to 20 per cent. of the heat in the fuel, or even more, due largely to radiation and the heat carried away in the gases.

The composition of various producer gases, as given by Prof. W. Robinson, is shown in Table XXIV.

Water Gas.—Water gas is largely used for admixture with coal gas, partly as a useful means of disposing of surplus coke, but also for dealing with peak loads, as a water gas plant can be started up from cold in three or four hours. It has been adopted for this purpose by a large number of gas undertakings and has the additional advantage, in its usual form, that the quality of the gas can be regulated easily to suit requirements.

Straight water gas is produced by passing steam over incandescent carbon, usually in the form of coke. In the lower part of the generator the oxygen of the steam combines with the carbon of the fuel to form CO_2 , H and CO, while in the upper part of the fire the CO_2 is reduced by the excess of glowing carbon to CO. These reactions absorb heat and will not take place if the temperature is below about 1100°F. , hence the operation of a water gas plant is divided into two parts, known respectively as the "blow" and the "run." During the blow period steam is shut off and air

TABLE XXIV

Composition and Calorific Power of Producer Gases.

Producer and fuel.	Composition—per cent. volume.						Cal. value B.Th.U.	Air per cub. ft. required cub. ft.
	H.	CH ₄ .	C ₂ H ₄ .	CO.	CO ₂ .	N.	O.	
Siemens, coal	8.6	2.4	—	24.4	5.2	59.4	—	134
Wilson, Durham coal	11.55	1.45	—	26.89	4	56.11	—	139
Lencauchez, Welsh anthracite	20	—	4	21	5	49.5	0.5	155
Dowson, anthracite	18.73	0.31	0.31	25.07	6.57	48.98	—	160
Riché, wood	44	12			22	22	—	336

blown in, resulting in the formation of a large proportion of CO_2 , with a considerable rise in temperature of the fuel bed.

The products of combustion are discharged directly to the atmosphere and not mixed with the gas. As soon as the necessary temperature is reached the air blast is shut off, steam admitted and gas-making commences. The quality of the gas gradually falls off as the run progresses and the temperature falls.

Many water gas plants are fitted with a carburettor, so that the gas may be enriched by means of vaporised oil.

The average compositions of carburetted and straight or "blue" water gas, as given by Mr. Alwyne Meade, are shown in Table XXV :—

TABLE XXV

	Carburetted water gas. Per cent.	Blue water gas. Per cent.
Hydrogen	35.0	52.0
Carbon monoxide	32.0	38.0
Carbon dioxide	4.5	4.5
Methane	13.0	1.0
Heavy hydrocarbons (C_mH_n).	10.0	Nil
Nitrogen	5.5	4.5
Calorific power (gross) B.Th.U. per cubic foot	580	300

The oil generally used for enrichment is petroleum residue, having a specific gravity of about 0.85.

There are a considerable number of different types of water gas plant, the best known being the Humphreys and Glasgow, K. and A. (Kramers and Aarts), and the Dellwik Fleischer, the first-named

being the one in most general use in British gas-works.

Water gas contains a large proportion of the poisonous carbon monoxide, and some objection has been taken to its employment in connection with town's gas on this account, but it is of considerable use, as mentioned above, on account of the ease with which it can be brought into use in case of a sudden increase in the demand for gas, and the relatively small number of men required to operate the plant.

Suction Gas.—A large number of small producer plants have been designed for the independent operation of gas engines. A supply of water vapour is produced by a quantity of water fed into the ashpan under the grate of the generator. These plants are so arranged that the quantity of gas produced is determined by the suction of the engine. A small hand-gearred fan is used for starting up the plant, but once the engine is set to work the generation of gas is automatic. Anthracite is the best fuel for this purpose, but coke and wood refuse are frequently used. In the latter case special arrangements are required for removing tar, which is otherwise liable to clog the valves of the engine.

The composition of a typical suction gas is given by Mr. Meade as follows :—

TABLE XXVI
Composition of Suction Gas

Hydrogen	.	.	.	.	16.0 per cent.
Carbon monoxide	.	.	.	.	34.0 „
Carbon dioxide	.	.	.	.	3.0 „
Nitrogen	.	.	.	.	47.0 „

The calorific value of suction gas is about 160 B.Th.U. (gross) per cubic foot.

Oil Gas.—Oil gas is made by the distillation of natural oil, either in retorts or by means of high-temperature steam. It was at one time largely used, as Pintsch gas, for the lighting of railway carriages in this country, but the use of oil gas for this purpose is now obsolete, and it is only used in those districts where oil is plentiful.

The yield of gas, when straight distillation is used, is about 22,000 cubic feet per ton of oil, or, when steam is used for cracking the oil, about 40,000 to 42,000 cubic feet per ton.

Oil gas has a specific density of 0·6 to 0·7 and a gross calorific value of about 1050 B.Th.U. per cubic foot. The average composition is: methane 45 per cent., hydrogen 25 per cent., and heavy hydrocarbons 30 per cent.

CHAPTER V

INDICATING AND RECORDING INSTRUMENTS

It will be seen from the foregoing chapters that the various fuels in common use require widely different volumes of air for their proper combustion, and in order to ensure that the correct amount of air is supplied various indicating or recording instruments are necessary.

The instruments generally adopted comprise draught gauges of various types, CO₂ indicators and recorders, temperature indicators and recorders, and in some cases air flow meters, and it is proposed to give some description of the various types of instruments and their uses.

Draught Gauges.—In many small plants the only instrument used is a simple draught gauge in the form of a U-tube of glass containing water or a coloured fluid, connected at one end by a pipe to the flue or furnace in which a reading of the pressure or depression is required, and at the other end open to the atmosphere. The difference in pressure between the gases in the flue and the external air is indicated by the difference in level of the liquid in the two legs of the U-tube. This difference of level is measured by a scale mounted between the two parts of the gauge, the scale being usually marked in inches or millimetres. Hence the intensity of draught is generally given as so many "inches (or millimetres) of water," or "inches (or millimetres) water gauge." One inch of water represents a pressure of 0.0361 pound per square inch or 5.2 pounds per square foot.

The type of gauge just described is not very sensitive, although very useful for ordinary purposes, and various modifications have been designed to give more accurate readings. One of the most common arrangements has the gauge tube inclined, by which means the variation in height of the liquid may be multiplied by an amount depending on the angle at which the tube is set.

A somewhat more elaborate pattern has one visible tube only, connected to a comparatively large reservoir of liquid, on to the surface of which the pressure to be measured is transmitted by the usual connecting pipe. The visible tube may be straight or curved, according to the pressure to be measured.

Hay's Draught Gauge, as supplied by the Duguid Instrument Supply Co., is an example of this type of gauge. Provision is made in the Hay gauge for checking the zero point and adjusting the level of the liquid by a micrometer levelling attachment, to make up for any loss of liquid due to evaporation.

Gauges of this type must be set truly level, and a spirit level is usually incorporated in the design.

In the "Full Scale" draught and pressure gauges of Messrs. Walker, Crossweller and Co., a vertical tube is used, connecting with a reservoir at the rear of much larger capacity than the tube, the proportions being so arranged that the rise and fall of the liquid in the tube is practically full scale.

Another pattern of gauge is based on the Bourdon principle, in which a bent flexible tube

of oval section is made to straighten more or less according to the pressure to which the interior is subjected. The movement of the free end of the tube is transmitted through gearing to a pointer which moves over the face of a dial. Gauges on this principle are made by the Cambridge Instrument Co., Ltd., and have the advantage that they are very easily read and are therefore suitable for mounting on the front of the boiler or furnace, where they can be readily seen by the attendant.

The types of draught gauges described above only give a point reading, and to obtain a definite idea of the variations in the draught readings must be taken and recorded at frequent intervals.

Various patterns of gauge are now made which record automatically any variations in the air pressure.

The Bourdon type of gauge mentioned above may be constructed as a recording gauge, the movement of the tube being transmitted to a pen which moves over the surface of a circular chart rotated by clockwork so that it makes a complete revolution in 24 hours, or in 7 days, as may be most convenient.

Another type of recording pressure gauge, made by various firms, consists of a cylindrical vessel containing oil into which an open-bottomed bell or float dips. A pipe communicates with the space between the top of the liquid and the closed top of the float. Any variations in pressure transmitted to this space through the pipe cause the float to rise or fall in the liquid, the motion of the

float being recorded by a pen on a chart wrapped round a drum carried in the upper part of the instrument and rotated by clockwork at a uniform rate. A gauge of this kind may also be used as an indicator by substituting a dial and pointer for the drum, with suitable gearing for converting the linear motion of the float into the rotatory movement of the pointer.

The standard ranges of these instruments are 0 to 2, 0 to 4, 0 to 6 or 0 to 12 inches of water, and they may be arranged, when required, to register the draught or pressure at two or more points at the same time.

Temperature Indicators and Recorders.—The simplest form of temperature indicator, and the one most commonly used, is the ordinary mercury-in-glass thermometer, and in many cases, where flues are accessible, they are very convenient, though somewhat fragile, and in dark situations difficult to read accurately. They can be obtained suitable for temperatures up to 1000° F., but as many furnace operations require temperatures very considerably in excess of this figure, other instruments are necessary in such cases.

Mercury thermometers can also be obtained with steel instead of glass tubes. In this case, as the expansion of the mercury is not visible, a Bourdon tube, with dial and pointer, is used, the movement of the tube being governed by the rise or fall of pressure in the system due to the expansion or contraction of the mercury under the changes of temperature. These instruments are more easy

to read than the ordinary pattern of thermometer, but the dial must be placed fairly near to the point where the temperature is measured.

When it is desired to observe or record the temperatures of various points in a plant at some central place, electrical resistance thermometers are very convenient. These instruments, which depend on the alteration in the resistance of a platinum wire with changes of temperature, can be used for temperatures up to 1000° F., and are accurate to within 1 per cent. of the range.

The current from a small accumulator flows through the platinum wire in parallel with a standard resistance, and any increase in the resistance of the platinum wire due to a rise of temperature causes a current to flow through a galvanometer, the pointer of which moves over a scale graduated to cover the working range of the instrument.

The Distance Thermometers of the Cambridge Instrument Co. are of the type just described and may be obtained with a multiple point switch embodied in the instrument, so that the temperature at various points of the plant may be observed by merely moving the switch arm on to the corresponding contacts. The indicator may be placed at any distance from the thermometer, to which it is connected by ordinary lead-covered cable, and a recorder may be used in conjunction with it, so that a visible record may be obtained of the changes in temperature.

Pyrometers.—The electrical resistance thermome-

ters described above are suitable for temperatures up to 540° C. (1000° F.), but for many industrial operations temperatures considerably above this figure are necessary. For temperatures up to 1200° C., platinum resistance pyrometers are the most suitable and are recommended where accurate measurements are required. Still higher temperatures, up to 1400° C., may be measured by thermo-electric pyrometers, while for temperatures above this figure optical pyrometers are more suitable.

Platinum resistance pyrometers depend on the variation with change of temperature in the resistance of a coil of platinum wire, which governs the current flowing in the arms of a Wheatstone bridge and so actuates the movement of a galvanometer needle, as in the electrical resistance thermometers. The Whipple Indicator of the Cambridge Instrument Company is a very accurate instrument of this type and is used as a standard for checking other patterns of pyrometer.

Thermo-electric pyrometers are extensively used for the measurement of high temperatures. The operation of these instruments depends on the fact that if two wires of different metals are joined at their ends and one of the junctions is heated, an electromotive force is set up in the circuit, the magnitude of which depends on the difference of temperature between the hot and cold ends of the wires. If a very sensitive voltmeter is placed in the circuit the movement of the pointer will depend on the E.M.F. and the current flowing in the circuit. The amount of E.M.F. set up for

each degree rise of temperature depends on the particular metals used for the couple. As the instruments record the difference of temperature between the hot and cold junctions, it is essential to keep the temperature of the cold junction as constant as possible, and this result is obtained in various ways, the most usual being by burying the cold junction some distance in the ground, or by immersing it in a vacuum flask filled with oil and surrounded by insulating material. In this way the temperature may be kept constant within 2 or 3 degrees.

Where it is not convenient to utilise one of these methods correct readings may be obtained by setting the pointer on the scale to the actual temperature of the cold junction before the hot junction is connected in circuit, or by utilising an electric thermostat which maintains constant the temperature in a box containing the cold junction.

The wires forming the thermo-couple are made of rare metals for the higher temperatures and of titan alloy, or iron-constantan for lower temperatures up to 1100° or 1200° C.

CO₂ Indicators and Recorders.—The ordinary CO₂ instrument depends for its operation on the fact that carbon dioxide is very readily absorbed by a solution of caustic potash. Hence if a measured volume of flue gases be drawn through or over a suitable solution and the volume of gases remaining be measured, the difference will indicate the actual volume of CO₂ present.

In the original Orsat apparatus, on which the

design of several other patterns is based, the gases are drawn through the potash vessel by means of a water aspirator. A measured quantity of gas, usually 100 cubic centimetres, is drawn from the flue. These gases are then driven through the potash solution, in which the CO_2 is absorbed, and the resultant volume of gases is measured, the difference giving the proportion of CO_2 in the gases.

By the addition of further vessels containing other reagents the proportion of oxygen and carbon monoxide can also be measured. These reagents may be a mixture of pyrogallie acid and caustic potash for absorbing oxygen, and ammoniacal solution of cuprous chloride for absorbing carbon monoxide. It is necessary to remove the CO_2 before passing the gases into the oxygen absorber, and to remove both CO_2 and O before determining the percentage of CO, as the oxygen solution will absorb CO_2 and the cuprous chloride solution will absorb both oxygen and CO_2 as well as CO.

The Hays Gas Analyser is an instrument constructed on the principles described above. The gas is drawn into a graduated vessel or burette by means of an aspirator bulb and the volume of gas is adjusted by means of a levelling bottle containing water and connected by a flexible pipe to the bottom of the burette, any surplus gas being exhausted to atmosphere through a cock at the top of the burette. The graduated tube is surrounded by a water-jacket in order to keep the

temperature of the gases constant. After the correct volume of gas is obtained, the levelling bottle is raised and the gas forced through the caustic potash vessel in which the CO_2 is very rapidly absorbed. By lowering the levelling bottle, the gas is then drawn back into the burette and the volume of gas is measured by adjusting the height of the bottle until the surfaces of the liquid in the bottle and the burette are level. The reading on the graduated scale then gives the percentage of CO_2 in the gases. The burette is then connected to the second vessel and the process repeated. The new reading gives the total volume of CO_2 and O, from which the percentage of O can be determined. A third repetition of the operation with the burette connected to the cuprous chloride vessel gives the percentage of carbon monoxide.

It is usually only necessary to take the CO_2 readings regularly, though it is advisable to take occasional readings of the other constituents as a check against incomplete combustion and leakage of air into the flues.

In connection with an analyser of the type described, an automatic gas collector is frequently used. This consists of a large closed vessel which is filled with water and provided with an automatic regulator, which ensures a regular and even sample of gases being obtained.

The Arkon Combustion Recorder of Messrs. Walker, Crossweller and Co. also depends on the absorption of CO_2 by a caustic potash solution,

but by means of a special syphon arrangement it is designed to take readings at regular intervals, while the percentage of CO_2 is recorded automatically at each operation on a chart revolved continuously by clockwork. Every analysis can also be checked independently by the readings of a graduated burette. The recorder is usually operated by means of a stream of water, but where this is inconvenient it may be driven by means of a small electric motor.

This instrument is only designed to measure the CO_2 percentage and is not fitted with the additional absorption vessels for determining oxygen and carbon monoxide, but it has the advantage that the measurement of the gas samples is quite automatic.

Both the instruments described above are constructed mainly of glass, and are therefore somewhat fragile. They are particularly useful for periodical tests on furnace performance, and the Arkon Recorder is also in extensive use as a permanent part of the boiler-house equipment in many factories.

Portable CO_2 indicators are also used where occasional tests only are required. Amongst these instruments may be mentioned the thermoscope of the Underfeed Stoker Co., Ltd., and the Roth CO_2 Indicator supplied by the Power Specialty Co., Ltd.

The Thermoscope depends for its action on the fact that when CO_2 is absorbed by caustic potash or soda, heat is evolved due to chemical reaction,

and the rise of temperature is proportional to the amount of CO_2 absorbed. The instrument consists of a double cylinder, the inner chamber being fitted with a plunger for drawing a sample of gas from the flue, while a special form of thermometer is mounted between the inner cylinder and the outer casing, in which a slot is cut to enable the thermometer to be read. This thermometer has a special hollow bulb, inside which is placed a cartridge of pulverised caustic soda, and the scale can be adjusted so that the zero mark is opposite the top of the mercury before a test is made. A second thermometer is inserted in the plunger for observing the temperature of the room, and the volume of gases drawn in is regulated by marks on the plunger corresponding to the room temperature, to ensure that a definite weight of gas is used for the reaction.

A sample of gas is taken by drawing out the plunger to the correct amount, and this gas is then driven through the cartridge, the ends of which have been pierced, by connecting a rubber tube from the nozzle of the cylinder to the cartridge chamber and pushing in the plunger. The rise of temperature of the cartridge, due to the absorption of the CO_2 , is imparted to the column of mercury in the thermometer, and the scale is graduated so that the percentage of CO_2 can be read directly from the height of the mercury.

The Roth CO_2 Indicator consists of a cylindrical vessel lined with silver and divided into two portions by a diaphragm. This diaphragm has a

central opening which may be closed by a plunger. The lower portion of the vessel contains the caustic potash solution and communicates at the bottom with a gauge glass, which is provided with a scale graduated in percentage of CO_2 . The gases to be analysed are drawn into the upper chamber of the vessel by means of an aspirator bulb, through a filter which serves to separate out any water and soot. When the chamber is full of gas, communication with the aspirator bulb and the flue is shut off by means of cocks and the plunger is lifted, allowing the gas to come in contact with the Caustic Potash. The CO_2 is absorbed by the potash solution, causing a partial vacuum which raises the level of the liquid in the chamber and lowers the liquid in the gauge glass. The reading on the scale shows directly the amount of CO_2 absorbed. The scale should, of course, be adjusted before any reading is taken till the zero mark is level with the top of the liquid in the gauge glass.

Another pattern of instrument largely used in this country is the W.R. CO_2 Indicator, made by W.R. Patents, Ltd. This instrument also depends on the absorption of the CO_2 by a reagent, which is inserted in the form of a cartridge every 24 hours. Gases are drawn continuously through the apparatus by an aspirator worked by the natural draught in the flue, and after passing through a filter to eliminate soot and dirt, these gases enter a chamber containing a porous pot, inside which is placed the reagent cartridge. Some of the gases pass through the walls of the porous pot and the

CO_2 is absorbed by the reagent, causing a partial vacuum, the amount of which is indicated on a gauge glass connected to the interior of the porous pot and to the gas chamber. The scale is graduated to read directly the percentage of CO_2 in the gases. Fig. 3 shows diagrammatically the construction of a W.R. CO_2 Indicator. A recorder

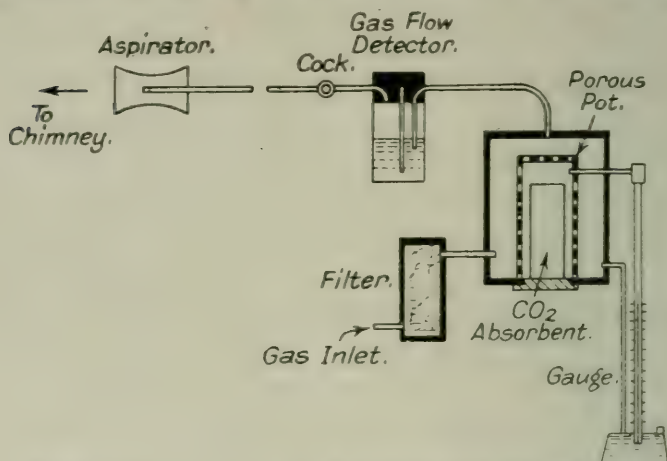


FIG. 3.—Diagrammatic Arrangement of W.R. CO_2 Indicator.

which shows the variation in CO_2 for a period of 24 hours can be connected to, or embodied in, the instrument when required.

An entirely different principle is employed in the electrical CO_2 indicators manufactured by the Cambridge Instrument Co., and other firms. It was discovered by Dr. Shakespear that if two similar coils of wire are heated by an electric current and immersed in cells containing gases of different thermal conductivities, heat will be transmitted

from the coils at different rates, and one coil will therefore be maintained at a higher temperature than the other. As the difference of temperature causes a difference in the resistance of the two coils, this variation may be made to operate the galvanometer of a Wheatstone bridge. Air and carbon oxide have different thermal conductivities, while the values for oxygen, nitrogen and carbon monoxide have nearly the same value as air, consequently the system described can be used to determine the proportion of CO_2 in the gases with considerable accuracy.

The electrical CO_2 meter, as made by the Cambridge Instrument Co., consists essentially of a metal vessel containing two cells in which are mounted the two platinum coils. One of these cells contains air and is entirely closed except for a connection to a small tube containing water, so that the air always remains in a moisture saturated state. The second cell has perforations through which the flue gases can enter after passing through a filter containing glass wool and iron filings in order to remove any soot and sulphur compounds. The metal containing vessel is connected into a pipe through which a constant stream of flue gas is drawn by means of a water or air aspirator. The stream of gas does not actually flow through the meter, but some of the gas diffuses into the cell through the filter as it passes the instrument.

The galvanometer and indicator which are operated by the thermal conditions in the two cells may be mounted at any convenient distance from

the meter, to which they are connected by a four-wire cable. The necessary current for operating the instrument is furnished by a small accumulator. The galvanometer, which is of the moving coil type, is mounted in the upper part of a water-tight iron case, which also contains the necessary switches and terminals, and a scale, graduated from 0 to 20, shows the percentage of CO_2 in the gases.

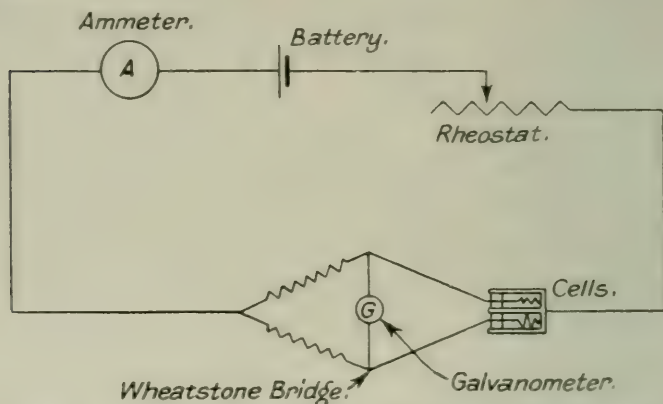


FIG. 4.—Diagram showing Operation of Cambridge Electrical CO_2 Meter.

The operation of the instrument is shown diagrammatically in Fig. 4.

Several meters can, if required, be connected to one indicator, so that, by means of switches, the condition of the gases at several points can be read from one central station, and instruments are also supplied which show the temperature of the gases at the same point simultaneously with the percentage of CO_2 , to enable the exact conditions of combustion to be determined.

The simple indicator is very suitable for use in the boiler house in order that the stoker may know the conditions of his furnace, but a separate recording instrument, operated on the same lines, but giving a continuous record of CO_2 and temperature, can be fixed in the manager's office or other convenient place. The recorder is connected permanently in circuit and the indicator only put in circuit temporarily by means of a push-button switch.

The recording of the amount of carbon monoxide and unconsumed hydrocarbons, together with a record of the percentage of CO_2 , affords the most complete information as to the conditions of combustion, and allows of the most accurate control of the furnace. An instrument which records alternately the percentages of CO_2 and combustible gases consequently offers advantages over the ordinary CO_2 recorder.

Such an instrument is the Duplex-Mono Recorder, manufactured by Messrs. James Gordon and Co., Ltd. In the Duplex-Mono recorder samples of the flue gases are drawn in by a mercury pump operated by water pressure or compressed air. On the return stroke of the pump the gas is passed through a measuring vessel and thence through a caustic potash solution in which the CO_2 is absorbed. The residue passes to a measuring bell, which by its rise and fall actuates the pen of the recording mechanism.

On the next stroke of the pump the measured sample of gas is passed through a small electric

furnace before it enters the caustic potash solution, in which the total amount of CO_2 and water, including the original amount in the gas and the further amount produced by the combustion in the electric furnace of any CO and hydrocarbons present, is absorbed. The residue is then passed into the measuring bell and the amount is recorded on the chart. The difference in height of two consecutive readings, which take place at approximately two-minute intervals, thus shows the proportion of combustible present in the gas.

The chart shows immediately the effect of any adjustment of the air supply. With too much air the percentage of CO_2 will be low and no CO will be recorded. If the air supply is insufficient, although the CO_2 will reach a higher figure, some combustibles will pass away with the flue gases and their presence will at once be shown on the chart. The draught and position of the dampers must therefore be regulated until the CO_2 is as high as possible with only the slightest traces of CO. This will give the maximum efficiency under the particular conditions obtaining in the furnace.

Volume Meters.—Where Gaseous Fuels are used it is important to know the volume of fuel which is passing to the furnace. As it is impossible to weigh such fuel, some form of volume meter must be used. For small volumes of gas, the ordinary displacement gas meter may be used, but for furnaces using producer, coke oven or blast furnace gas, where the volumes handled are considerable, some form of continuous flow meter must be used.

A Pitot tube may be used for determining the volume of gas flowing in a tube. If a U-tube water gauge has one leg connected to a pipe inserted into the air duct with its end turned towards the air-stream, while the other leg of the gauge is connected to a similar pipe having an opening at right angles to the air-stream, the difference of level of the water in the two legs of the U-tube will indicate the velocity head. From this reading the velocity of the air or gas can be determined, together with the volume of gas which is being delivered. By suitable arrangements, the volume of gas can be read directly. As the velocity of gas flowing in a pipe varies across the diameter, it is necessary, if accurate readings are required, to arrange the Pitot tubes at a certain distance from the side of the pipe. There is also a liability of error due to inductive effects produced by the flow of air over the apertures in the tubes, and for most practical purposes other forms of volume meter are used.

The most common types of volume meter depend on the difference of pressure found on the two sides of a throttle plate or nozzle inserted in the main, as in the Arkon meters, or in a convergent-divergent pipe, as in the Venturi meters manufactured by Messrs. Geo. Kent, Ltd.

The difference of pressure set up on the two sides of a throttle plate depends on the velocity and density of the fluid and on the shape of the orifice. As the density of the fluid is generally more or less constant and the effect of various forms of orifice is accurately known, the velocity can easily be deter-

mined, and from this the volume of fluid passing through the orifice. The throttle plate may be either a plain plate with a circular hole of definite size in relation to the diameter of the pipe, or a smooth cone, and whichever form is used it should be placed in a straight length of the main where the flow is uniform.

The difference of pressure on the two sides of the diaphragm is transmitted to a weighted bell suspended in water or other suitable liquid. The bell rises or falls in unison with the variations in pressure, and the motion is transmitted either to a pointer moving over a circular dial or to a pen which records the movement on a chart revolved by clockwork. The pressure difference varies actually as the square of the velocity, and consequently of the volume, and it is therefore necessary to have a chart graduated to a logarithmic scale, or, as in the case of the Arkon meter, to have a bell of special shape in which the movement is directly proportional to the velocity.

The throttle plate method causes a slight loss of pressure, and if it is important to avoid such loss, a Pitot or Brabbée tube must be used to measure the velocity.

The Venturi meter is based on Bernouilli's theorem, which shows that the total head in a stream of fluid of gradually varying section remains constant. In the case of heavy fluids such as water, it is advisable for a Venturi meter to be placed horizontally, but in the case of light fluids, such as air or gas, this point is not so important.

as the difference in pressure due to a difference in the level of the two points to which the gauge is connected is negligible for the comparatively short length occupied by the Venturi pipe.

The general arrangement of a Venturi meter is shown in Fig. 5. One leg of the gauge is connected to the large portion of the pipe immediately in front of the convergent portion, and the other to

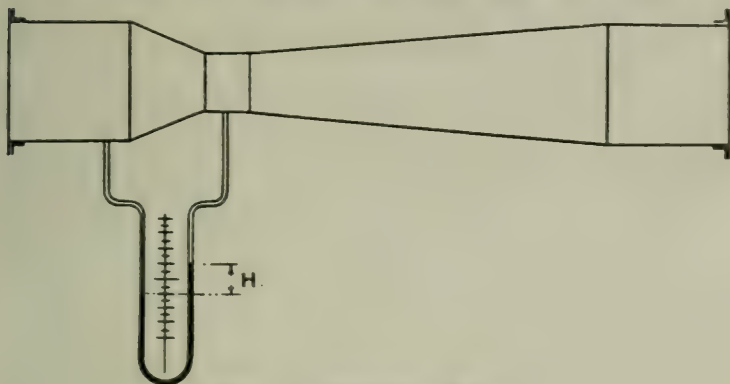


FIG. 5.—Venturi Meter.

the centre of the throat or smallest portion of the meter. The difference in the levels of the liquid in the two legs of the gauge indicates the difference of pressure due to the increase of velocity of the fluid. As in the case of the throttle plate, the velocity head varies as the square of the velocity, hence the scale showing the velocity must be graduated logarithmically, or a table must be used from which the velocity or volume can be read directly from the actual difference of level of the liquid. The pressure may also be transmitted to an indicator or recorder with a bell of special

shape as in the case of the Arkon meter described above.

The loss of pressure in a Venturi meter is very small if the pipe is of the correct shape and made perfectly smooth inside. It is important that the areas of the large and small portions be accurately known, and there must be a sufficient length of straight pipe in front of the convergent portion to prevent the formation of eddies.

Measurement of Solid Fuels.—In order to determine the efficiency of any furnace using solid fuel, the weight of fuel used must be known with accuracy. This weight may be determined in several ways, either by direct weighing or by measurement. Automatic weighing machines, which weigh continuously the amount of coal fed into the hoppers of automatic stokers, have been in use for many years. These machines, as made by Messrs. Avery, Ltd., comprise a hopper supported from a scale and so arranged that as soon as a pre-determined weight of coal enters the hopper, the supply of coal is shut off and a door in the bottom of the hopper is opened and the coal discharged into the stoker. The emptying of the hopper allows the door to close and the supply of coal to the hopper to be restarted. This operation is repeated continuously, and the total weight of coal is recorded on a counter which shows the number of times the weighing has been repeated.

Other automatic weighing machines are used for recording the weight of coal carried by band conveyors and by electric transporters or telfers, but

the machines only give a general check on the total quantity of fuel consumed, and do not check the amount fed to each individual furnace.

For small plants, the fuel is generally weighed by hand. A different method is used in the Lea Coal Meter supplied by the Lea Recorder Co., Ltd., who have found that equal weights of coal of widely different grades occupy practically the same volume. The Lea coal meter is arranged to measure the volume of coal passing to the furnace, by means of a spirally toothed drum having a pitch proportional to the maximum lift of the door admitting the coal to the furnace. A counting wheel driven by gearing from the spiral drum is mounted on a rod connected with the fire-door. As the fire-door is opened to a greater or less extent the counting wheel is moved to and fro across the spiral drum, which causes it to revolve more or less according to its position on the spiral. The amount of revolution of the counting drum is therefore proportional to the amount by which the fire-door is opened, and consequently to the thickness of the stream of coal, which is directly proportional to the weight. The revolutions of the counting wheel are multiplied by a constant which gives directly the weight of coal burnt. If widely different qualities of fuel are used, it is advisable to determine the constant for each class of coal, but in practice it is found that the variation between different classes of slack is so small that one constant is sufficiently accurate for ordinary purposes. In a test on coal from seven different collieries it was

found that the variations from the constant determined for one coal ranged from -2.4 per cent. to $+6.9$ per cent.

Calorimeters.—The calorific value of any fuel may be obtained by calculation in the manner previously shown, provided its chemical composition is accurately known, but it is advisable to check the actual value from time to time by means of a calorimeter, and in the case of tests on any furnace it is usual to determine the heating value in this way. In gasworks, where it is now the usual practice to sell gas by its thermal value, a calorimeter operating continuously is used to show the actual value of the gas which is being sent out from the works.

The actual type of calorimeter used depends on the nature of the fuel. For solid fuels, and sometimes for liquids, the bomb calorimeter, or a modified form of it, is adopted.

The bomb calorimeter, of which there are various patterns, consists essentially of a strong metal vessel immersed in water, a known weight of the fuel being ignited electrically and burnt in an atmosphere of oxygen. The heat evolved during the combustion of the fuel is measured by the rise in temperature of the water.

About 1 gramme of the fuel is placed in a platinum crucible and accurately weighed. The crucible is suspended in the inner steel vessel and the cover tightly screwed down. Two copper rods project into the vessel, by means of which an electric current can be sent through a piece of fine iron wire of known weight which dips into the fuel

in the crucible. Oxygen is admitted into the bomb at a pressure of 300 to 375 pounds per square inch and the inlet valve closed. The bomb is immersed in water in a copper vessel, which is again placed in an outer water-jacket in order to prevent loss of heat by radiation as far as possible. A stirrer is arranged in the calorimeter so that the temperature of the water may be kept uniform. The temperature of the water is carefully noted for two or three minutes until it remains steady and is the same as the temperature of the bomb. An electric current is then passed through the iron wire until the latter is raised to white heat, when the fuel is ignited and burns practically instantaneously. The water in the calorimeter is continuously stirred and the temperature noted carefully every half minute until it has reached a maximum and begins to fall. The rate at which it falls is an indication of the loss by radiation, which should be taken into account when estimating accurately the amount of heat evolved from the combustion of the fuel.

The weight of the calorimeter and the water, multiplied by the appropriate specific heats and by the rise in the temperature, gives the total amount of heat generated by the combustion of the fuel. The heat due to the combustion of the iron wire must be deducted, at the rate of 1575 calories per gramme. The remainder, divided by the weight of the fuel, gives its calorific value. The figure obtained in this way is the gross calorific value, that is, it includes the latent heat of any steam formed by combustion of the hydrogen content of the fuel, as

the steam condenses on the walls of the bomb and therefore gives up its latent heat.

The Junkers Calorimeter, used for determining the calorific values of gaseous fuels, consists of a combustion chamber surrounded by a water-jacket through which pass a large number of thin copper tubes, communicating at their upper ends with the top of the combustion chamber and at the lower end with an annular space provided with an outlet for the products of combustion. Water flows upwards through the jacket at a constant rate and the rise of temperature is measured by thermometers inserted in the water inlet and outlet connections. The gas is usually measured by a small meter, reading to 1/100 cubic ft. with the pressure maintained constant by means of a governor. The rate of flow is maintained constant by means of supply and overflow tanks which are fixed at a definite height above the apparatus. Any steam formed collects at the bottom of the annular space into which the copper tubes discharge and is run off into a graduated measure. For accurate readings, the temperature of the gas and the barometric pressure should be taken during the test. Assuming that V is the volume of gas burned during the test, W the weight of water in pounds passing through the jacket in the same time, w the weight of condensed steam collected and t the steady temperature rise maintained in the water, the total amount of heat generated is Wt B.Th.U., and the calorific value of the gas is $\frac{Wt}{V}$ per cubic foot.

The nett or lower calorific value of the fuel is

obtained by deducting the latent heat of the steam formed during the combustion of 1 cubic foot of gas, which is given by $\frac{966w}{V}$.

To reduce radiation losses to a minimum the calorimeter has a polished or plated surface and is contained in an outer closed casing forming an air-jacket round the calorimeter proper.

The Junkers calorimeter may be used for determining the calorific value of liquid fuels by using a special form of burner in which the liquid passes through a coil, heated by the flame, in which it is vaporised. The oil is forced through the burner by air pressure produced by a small pump, and in one pattern of calorimeter the weight of fuel burned is measured by suspending the burner with the coil and tank from a balance. After conditions have become constant, a suitable weight is removed from the pan and the test is carried out until the pointer of the balance returns to zero.

It must be noted that the heat evolved during combustion at constant pressure, as in the Junkers calorimeter, is less than that generated in the bomb calorimeter, where the combustion takes place at constant volume with a considerable rise of pressure. The latter form of calorimeter gives the maximum value of the heat evolved by the combustion of a given weight of any fuel.

The Thomson calorimeter is used for solid or liquid fuels and is somewhat similar in construction to the bomb calorimeter, but the combustion takes place at approximately atmospheric pressure and does not require a heavy bomb.

The Rosenhain calorimeter, manufactured by the Cambridge Instrument Co., Ltd., is an improved form of Thomason instrument. It consists essentially of a glass vessel in which the sample of fuel is burned, and an outer vessel containing water. The combustion chamber is a glass cylinder closed at top and bottom by metal clamping plates held together by three screws. The upper plate is provided with a tube for admitting oxygen and a second tube carrying the electrical ignition connections. The combustion gases pass out into the water through a non-return ball valve, which prevents water from entering the combustion chamber, but a small amount of water can be admitted when required, this water being forced out by the oxygen in order to ensure that the whole apparatus is at the same temperature.

On ignition of the sample of fuel, which is placed in a silica dish, the gases pass out through the ball valve and bubble through the water, imparting heat to it and keeping it well agitated. The pressure in the combustion chamber cannot rise appreciably above that corresponding to the depth of the water in the calorimeter, and the pressure of the oxygen need only be slightly higher, to ensure a regular supply to the fuel. The whole instrument is enclosed in a wooden case, with suitable apertures for observing the reaction, in order to minimise radiation.

Liquid fuels may be tested in this instrument by the use of absorbent pellets, which take up a considerable bulk of liquid and burn without residue.

The calorific value of the pellets, which is accurately known, must, of course, be deducted before determining the heat evolved by the fuel.

Various types of continuous-acting indicating or recording calorimeters are used for showing the thermal value of the gas sent out by gasworks, and may be used for any gaseous fuel.

They usually comprise, as in the Simmance calorimeter, a small governor for regulating the pressure of the gas, a meter for indicating the amount of gas passing through the instrument (generally 1 cubic foot per minute), and a burner, the heat from which operates the indicating or recording mechanism by means of the expansion of a copper rod or a thermostat.

The governor regulates the volume of gas in accordance with its density and the barometric and temperature conditions, so that no corrections have to be made from the figures shown by the instrument.

Many other types of indicating and recording instruments are in use, but the examples which have been given will be sufficient to show the possibility of controlling closely the working of any furnace in order to maintain the efficiency at a high level, and the principles which govern the operation of the various types.

The construction and principles of draught gauges will be considered more fully in a subsequent volume dealing more particularly with the question of furnace draught.

CHAPTER VI

PRACTICAL CONSIDERATIONS

IN the foregoing chapters, the general principles governing the combustion of various fuels have been set out, together with some account of the various classes of fuel and the various types of instruments used for determining the conditions of combustion.

It is now proposed to give some general notes on the conditions which should be observed if the best results are to be obtained.

In many small power plants no control instruments are used and the whole operation of the furnace depends on the knowledge and skill of the fireman. A skilful stoker will maintain the fire in a good condition, with an even fuel bed and without making any appreciable amount of smoke. A poor fireman, on the other hand, may allow holes to appear in the fire, admitting large quantities of cold air, and seriously reducing the efficiency of the boiler, so that he has difficulty in maintaining the steam pressure, and in his efforts to bring up the steam pressure throwing on to the fire large quantities of fresh fuel, with the result of further cooling the fire and producing a large amount of smoke.

It is important that an even fire be maintained and the fresh coal either sprinkled evenly over the fire or fed on to the dead plate just inside the furnace door and gradually pushed forward into the furnace as the volatile constituents are distilled off, so as to maintain the fire of an even thickness and

uniformly incandescent. The supply of air must be carefully regulated in accordance with the requirements of the fire.

It must be understood that in the ordinary small boiler plant the furnace acts generally as a gas producer, and that the gases leaving the surface of the fuel bed are actually combustible producer gases. This is due to the fact that the air entering the fire through the grate is insufficient for the complete combustion of the fuel, the oxygen of the air being consumed before it has passed through much more than the lower half of the fuel. In the upper layers of the fire the CO_2 first formed is partly reduced to CO and is mixed with hydrocarbons distilled from the upper portion of the fuel. The gas is therefore becoming richer in combustible constituents as it rises through the fuel bed.

The reduction of the CO_2 and the rate at which the volatiles are distilled off depend on the temperature of the fire.

Soot and tarry matters form a large proportion of the combustibles leaving the fire, and if there is insufficient air present for their complete combustion, some of these products will leave the boiler as smoke. If the bars are partly made up with ash and slag, the supply of air will be reduced and the fire will become dead. The bars should therefore be kept clear in order to allow as much air as possible to pass into the fire, and a supplementary supply of air must be admitted above the fire. This additional air is usually admitted

through dampers in the furnace door, or the door itself is kept slightly open, while in some types of furnace air is admitted through the bridge at the back of the fire. In any case, ample space must be allowed in the combustion chamber, and the supplementary air should be admitted in thin streams at a high velocity in order to effect complete admixture with the gases. Admission of air at the furnace

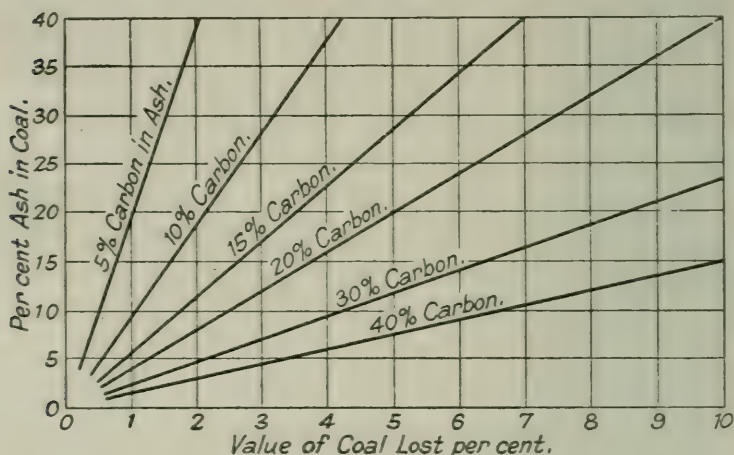


FIG. 6.—Loss in Heating Value of Coal due to Unconsumed Carbon in Ash.

door is preferable to its introduction at the bridge, as in the latter case combustion must take place in the flues instead of in the furnace, but a small supply at the bridge is of use in ensuring that all traces of combustible are burnt.

The importance of ensuring the complete burning of the whole of the combustibles is shown in Fig. 6, which gives the percentage of fuel lost for various proportions of carbon remaining in the ash removed from the ashpit of the furnace.

With ordinary furnaces it is difficult, even with forced draught, to admit all the air required through the bars, but the intensity of the draught does have an important effect on the *rate* of combustion. The amount of coal burnt is directly proportional to the weight of air forced through the fire.

A fire thickness of 8 or 10 inches is sufficient for ordinary duty. It is possible, in the case of boilers provided with a mechanical draught system, to control the air supply automatically, thus relieving the stoker of a large part of the work which requires skill and knowledge, and at the same time to save an appreciable amount of fuel. The method of effecting this automatic control will be described in a future volume dealing more particularly with the question of Mechanical Draught.

The installation of mechanical stokers is also an effective means of securing economy of fuel, as by their use the conditions of combustion may be kept constant and the necessity obviated for constant regulation of the air supply.

With mechanical stokers the thickness of fire and rate of feed must be adjusted by trial to suit the particular coal in use. In general, the thickness should be reduced as the proportion of small coal increases, and the rate of feed, or in the case of a chain grate the speed of the grate, must be adjusted so that all the coal is completely burnt on reaching the end of the grate. A bright fire must be maintained under the arch. Messrs. Babcock and Wilcox, Ltd., state that in the case of their chain grate stokers, with the driving shaft

running at the standard speed of 50 r.p.m., and with a draught of $\frac{1}{2}$ inch water gauge, the fire thickness should be $2\frac{1}{2}$ to $3\frac{1}{2}$ inches for small coal, and 4 to 5 inches for nuts.

With a stronger draught, the thickness should, of course, be greater, or an excessive amount of air may be drawn through the fire.

Sufficient tension should be kept on the chain to ensure that the top surface is level.

Any furnace consists essentially of two parts, the fire grate or burner and the combustion chamber. In a perfect furnace burning solid fuel, all the fuel will be consumed to a pure ash and no unburnt particles will be allowed to fall between the bars or be drawn out when clearing the fires. It is not possible to carry out this ideal in its entirety, but many mechanical stokers approach the ideal very closely.

The combustion chamber should not be too high, but should be of sufficient length to allow combustion to take place fully before the gases are cooled by giving up heat to the boiler tubes or furnace brickwork.

With pulverised coal, gaseous and liquid fuels, it is possible to effect practically complete combustion of the fuel, with the production of a very high temperature, due to the intimate admixture of the air and fuel with a consequent reduction in the amount of excess air necessary.

If possible, the gases should in their travel be exposed to a mass of incandescent brickwork, as with this arrangement and a properly regulated

supply of air, no gases are likely to pass away unburnt. Where pulverised, liquid or gaseous fuels are used this brickwork is essential, as there is no mass of fuel to retain heat, and in the event of momentary stoppage of the fuel supply, there will not be sufficient heat to re-ignite the fuel when the supply is resumed, unless it comes in contact with incandescent brickwork.

In the case of steam boilers, it must not be forgotten that the transmission of heat through the furnace plates or tubes is very much more rapid at high than at low temperatures, and is proportional to the difference between the temperature of the steam and that of the gases.

Fig. 7, drawn from figures published by Mr. Bryan Donkin, shows the variation in rate of evaporation in a locomotive boiler as the gases are cooled during their passage from the fire-box to the smoke-box.

It will be seen from this figure how important it is to maintain the temperature in the furnace as high as possible in order to obtain the maximum evaporation from the combustion of the fuel. This can only be effected by a proper regulation of the draught and the air supply. With good Welsh coal and an excess of air over that theoretically required of 50 per cent., the temperature of combustion will be about 3000° F.

As has been shown previously, the supply of heated instead of cold air for combustion will give a higher furnace temperature, and the provision of a suitable preheater will show a considerable

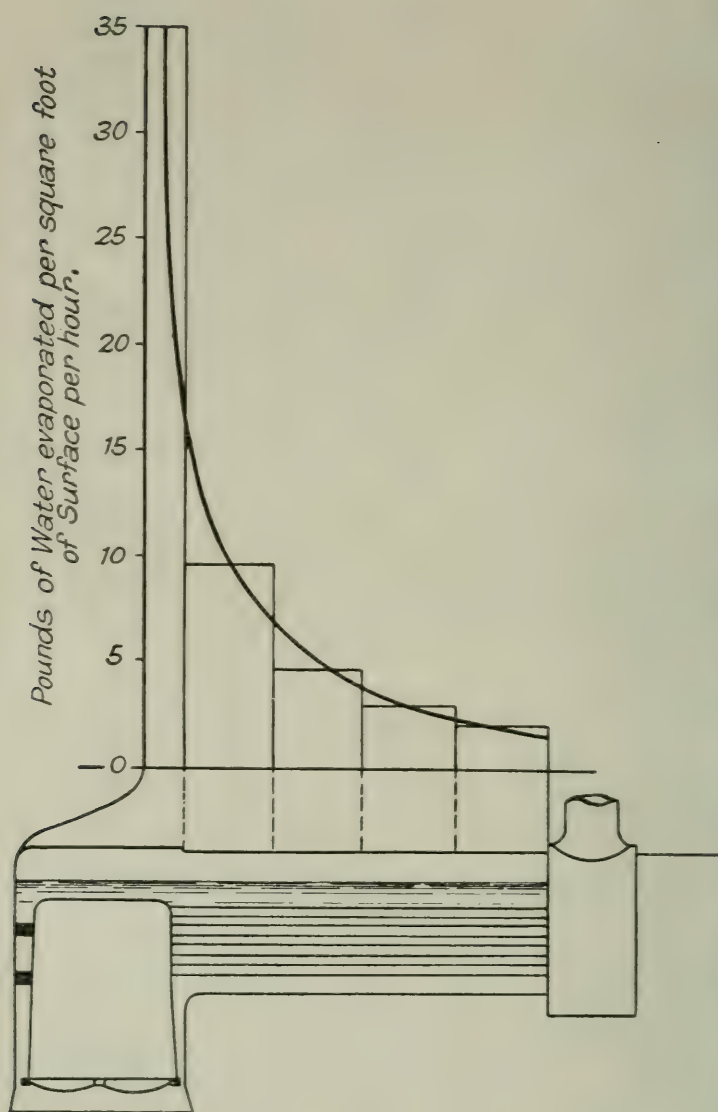


FIG. 7.—Effect of Temperature of Flue Gases on Heat Transmission and Evaporation in a Steam Boiler.

economy, due to the reduction in the loss of heat passing away up the chimney. Where such an arrangement is installed, mechanical draught is necessary, owing to the reduction of the gas temperature and the additional resistance offered by the heater.

By reducing the temperature of the flue gases from 750° F. to 350° F. in the air heater, an economy of 12.3 to 16.8 per cent. of the original heat in the coal can be recovered, according to the amount of excess air. If the temperature is reduced from 470° F. to 350° F., the heat recovered is from 3.9 to 5.4 per cent. An air heater has a very high efficiency, generally 92 to 95 per cent., as the only loss is that by radiation from the outside of the heater, which may be reduced to a minimum by arranging the air and not the flue gases immediately next to the casing. The air may be heated from 90° to 375° F., according to requirements. Tests have shown that approximately 10 per cent. greater saving may be effected by the use of an air heater than by the more usual economiser, while by the use of both economiser and air heater about 20 per cent. may be saved. This last arrangement gives the maximum recovery of heat and also gives a high feed temperature to the boiler. Fig. 8 shows the effect of the temperature of the flue gases on the loss of heat from the furnace, with various percentages of CO_2 .

In the fire-box of a steam boiler a large proportion of the heat transmitted is due to radiation, but in the tubes it is due to conduction, and the

velocity of the gases through the tubes has an important effect on the rate of heat transmission. To obtain the best effect the area of the tubes should be small, so that a high velocity of the gases is obtained.

Prof. Osborne Reynolds and Dr. J. T. Nicholson have shown that the amount of heat transmitted

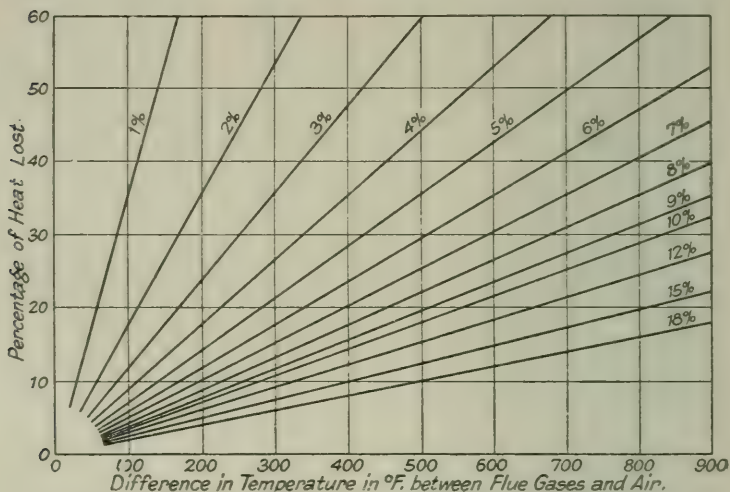


FIG. 8.—Losses due to Temperature of Flue Gases.

(Diagonal lines show percentage of CO₂ in flue gases.)

from the flue gases to the water is directly proportional to the weight of gases passing per square inch of cross-sectional area of the tubes and to the difference of temperature between gases and water.

Insufficient combustion space is a source of smoke, but the entire combustion of the soot will not necessarily increase the efficiency of the furnace, especially for steam raising, where a luminous,

highly radiative flame seems essential for the maximum production of steam.

Dr. J. T. Nicholson has shown that the most economical rate of combustion in ordinary furnaces

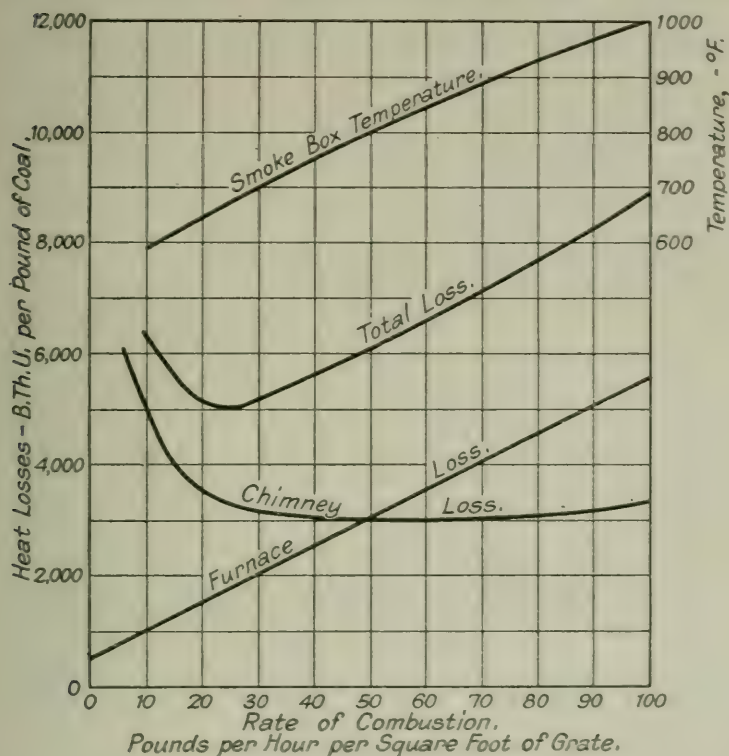


FIG. 9.—Furnace and Chimney Losses.

Ordinary Boiler — $\frac{\text{Heating Surface}}{\text{Grate Area}} = 40$.

is between 25 and 30 pounds of coal per square foot of grate area per hour. At lower rates more perfect combustion may be obtained, but the chimney loss is usually high, due to the large amount of air supplied to the furnace. At higher

rates of combustion the chimney loss decreases, but imperfect combustion and the loss of fuel drawn through the flues by the strong draught more than counterbalance the saving in the chimney losses.

This is shown diagrammatically in Fig. 9.

Fuel should be fed to the furnace in the driest

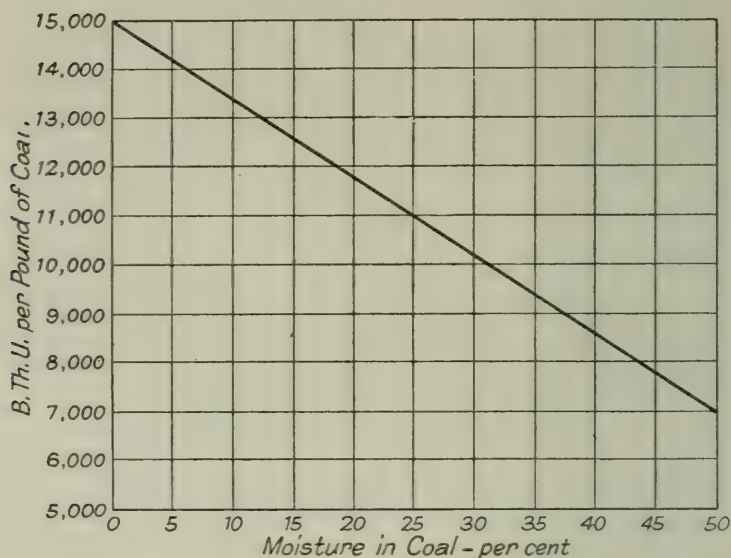


FIG. 10.—Effect of Moisture in Coal on Heat available for Useful Work.

possible condition, and it is therefore advisable to store it under cover when this can be done conveniently. The heat absorbed in the furnace in evaporating the moisture and superheating the resultant steam amounts to 12.5 B.Th.U. per pound of coal for each 1 per cent. of moisture present.

It is, however, advisable in some cases, where

coal must be stored for long periods before use, to keep it under water in order to prevent the gradual oxidation which must take place when the coal is exposed freely to the air. It should, of course, be dried as far as possible before use.

Fig. 10 shows the effect of moisture in the coal in reducing the heat available for useful work.

Pulverised Fuel.—The use of solid fuel in a very finely divided form is becoming more common, and for certain purposes this method of burning fuel effects great economies, in spite of the fact that a considerable amount of power is required for the preparation of the coal.

In the first place, many finely-divided and low-grade fuels which for various reasons cannot be burnt satisfactorily on an ordinary grate can be burnt quite well if they are further ground and blown into the furnace with a suitable amount of air. This is due to the fact that in a finely-divided state the coal offers a very greatly increased surface to the action of the oxygen in the air. With coal ground to the usual degree of fineness, where 85 per cent. will pass through a sieve having 200 meshes to the linear inch, or 40,000 to the square inch, the total surface of the particles is about 350 times that of the same coal in small lumps, say about 1 inch cube. On this account, the coal burns with extreme rapidity and completely, with a much smaller volume of air than would be necessary for combustion in the ordinary type of furnace.

The amount of excess air used is approximately

25 per cent., hence the furnace temperature is very high and the transfer of heat is more rapid and complete than with the usual furnace. The actual flame temperature is about 3100° to 3300° F.

There is practically no loss of unconsumed fuel, and owing to the comparatively small volume of air used, the chimney losses are also low. As the fuel is usually dried, during preparation, till it contains less than 5 per cent. of moisture, a further saving of heat is obtained, and the furnace temperature increased, due to the small amount of heat required for evaporating the moisture and superheating the steam.

Apart from the actual saving in fuel, which is approximately 25 per cent. (in annealing furnaces a saving of 60 per cent. has been effected), there is the additional advantage of being able to use classes of fuel which are generally regarded as useless or uneconomical.

Owing to the high flame temperature, the question of furnace linings is very important. Most of the ordinary materials used for lining furnaces melt at or below the flame temperature of powdered fuel, and it is therefore necessary to protect the lining as far as possible by preventing the flame from impinging on it. Carborundum has proved one of the most efficient refractories for this duty, but is expensive and is only used for the most important positions, or as a facing to a less expensive material.

Ample furnace capacity is necessary, so that the fuel may be completely burnt before it comes into

contact with the boiler tubes or other material which can chill the gases. The velocity of the gases through the furnace and boiler should not exceed 10 feet per second.

The danger of explosions of the coal dust may be obviated by proper design of the apparatus in order to avoid leakage of dust, and by using less air for the feeding of the fuel into the furnace than is necessary for combustion, the additional air being introduced at the burner or through secondary ports in the furnace.

Trouble has been experienced by the fusing of the ash into slag, but this can be overcome by proper regulation of the air supply and, in boiler plants, by the provision of a water tube screen or lining to the lower part of the furnace, in order to chill the ash rapidly and prevent its fusion into slag. Readers who are particularly interested in this branch of the subject are referred to Mr. Leonard C. Harvey's book "Pulverised Fuel, Colloidal Fuel, Fuel Economy and Smokeless Combustion."

Oil fuel also has similar advantages to powdered fuel, insomuch as the finely atomised oil can be very intimately mixed with the air with the necessity for a small excess of air only and the production of very high temperatures. Oil has the further advantage of occupying a relatively small space for storage and the labour required for the operation of the furnace is reduced to a minimum.

Gaseous fuel can be very conveniently used in many cases, especially where large quantities of combustible gases are available, as in the case of

blast furnaces and coke ovens. The supply of gas and air is under complete control, enabling the temperature of the furnace to be regulated within very close limits, and the flame may be made oxidising, reducing or neutral as required. Perfect combustion can be obtained without the production of smoke, and where particularly high temperatures are required, both gas and air may be preheated.

Blast furnace gas has been burned successfully with only 10 to 15 per cent. excess air.

Where waste gases are not available, cheap qualities of fuel can be used for the generation of the gas in producers, and the gas can, where required, be burnt directly in internal combustion engines for the production of power.

Prof. Wheeler has shown that for the heating of furnaces in steel works and for similar purposes, gases rich in carbon monoxide are preferable to those having a high proportion of hydrogen.

This is due mainly to the fact that the flame produced by the combustion of hydrogen has a rate of movement or propagation about eight times that of the flame produced by the combustion of carbon monoxide, and hence the flame in the former case is very much shorter, and combustion may, in extreme cases, take place within the ports or burners themselves.

The greater part of the heat received by a furnace charge is due to radiation from the flame and from the heated walls and roof of the furnace. Although carbon monoxide and hydrogen have practically

the same calorific value, the CO flame radiates nearly $2\frac{1}{2}$ times as much heat as the hydrogen flame, hence a gas rich in CO is preferable for furnace work as there will be a more effective transference of heat to the charge.

There is not a very great difference in the range of proportions of gas and air forming a combustible mixture, though hydrogen has a slight advantage in this respect. In contact with heated brickwork, the rate of combustion of hydrogen is very much greater than in the case of carbon monoxide, and the local temperature produced is therefore much more intense in the case of gases rich in hydrogen.

The presence of methane (CH_4), which is an important constituent of certain gaseous fuels, has also a considerable effect on the rate of propagation of the flame, reducing the velocity to an even greater extent than CO.

By a suitable mixture of gases, or by varying the proportion of steam and air in the producer blast, the character of the flame can be greatly modified to suit the requirements of the furnace, and the furnace losses can be reduced considerably.

The presence of a considerable quantity of hydrogen leads to further losses, on account of the fact that steam is formed on combustion, and owing to the relatively high specific heat of steam an excessive amount of heat is carried away in the flue gases.

Surface Combustion.—It has been found that a mixture of gas and air forced through a porous

diaphragm of refractory material can be made to burn within the pores of the diaphragm, which is thereby raised to a very high temperature. The air and gas are supplied under considerable pressure, with only a slight excess of air, and the mixture passes from the mixing chamber through the flat, porous diaphragm. Shortly after ignition the flame which first issues from the diaphragm disappears, and combustion takes place within the pores of the material, which attains a bright orange or white heat. Steam boilers fitted with this form of furnace have shown efficiencies up to 90 per cent.

Waste Heat Boilers.—In many works where large quantities of fuel are consumed for the heating of furnaces and retorts, sufficient heat may be obtained from the waste gases for generating all the steam required for the production of power, lighting and heating, thus saving the combustion of a considerable amount of fuel, and in many cases giving a handsome return on the outlay necessary for the provision of suitable plant. These remarks apply particularly to steelworks, gasworks, coke oven plants and cement works.

It is necessary to instal boilers designed specially for the purpose of utilising the heat in waste gases and also to restrict the amount of air supplied to the furnaces to a reasonable amount in order to maintain the temperature of the gases as high as possible. According to Mr. J. N. Williams (*The Gas World*, February 21st, 1925), it is possible to generate in a suitable boiler working on the waste

gases from retort settings approximately 5 pounds of steam per pound of fuel fed into the producers after the gases have done their work in heating the settings. This figure approaches very closely the average evaporation in direct-fired Lancashire boilers, as given by Mr. David Brownlie from the results of tests in 100 boilers, and similar figures may be obtained in other works where large quantities of waste gases are now being allowed to escape directly to the chimney-stacks. Owing to the reduction in the temperature of the gases in the boiler, and also to the additional resistance imposed by the boiler, it is necessary to increase the draught by means of an induced draught fan.

The temperature of the waste gases may be as high as 1100° F., while on leaving the boiler they may be reduced to 600° F., or if an economiser is also installed, about 400° F.

Precautions to be taken in Flue Controls.—When installing any types of furnace control instruments which depend on accurate samples being taken of the flue gases, there are certain necessary points to be observed, otherwise the results of the tests may be misleading. The principal points to be watched are given below.

Flue Gas Analysis.—The gas inlet pipe to the testing apparatus, of whatever kind this may be, should be placed in such a position that it will draw in a true sample of the gases. In a horizontal flue there may be differences in the composition of the flue gases at various levels due to the lighter and hotter portions of the gases rising to the top

of the flue, while in a vertical flue the mixture will be practically uniform. It is advisable, therefore, that the gas inlet pipe should be placed in a vertical portion of the flue. It should not be placed near a bend in the flue and should be fixed as far as possible from a damper or access door where there may be leakage of air, and from any sudden change of section of the flue, where eddies may be caused.

Flue Gas Temperature.—The same precautions should be taken as for analysis, and the thermometer should preferably be placed near the gas intake pipe, so that readings are taken on both instruments under similar conditions.

Draught.—The draught gauge should be connected to the flue away from any point where there may be eddies or sudden changes in velocity. If the gauge is connected into the flue at a level appreciably different from that of the furnace, the difference in height must be taken into consideration. If the gauge is connected at a higher point it will record a draught less than the true reading at the furnace level, due to the natural draught produced by the column of heated air. Conversely, if it is at a lower level it will show an increased draught due to the same cause. Under ordinary circumstances, there is not likely to be much difference in the readings, but in modern water tube boiler plants the flue leading from the boiler or economiser may be at a considerable height above the furnace, and this point may become of importance.

The recording of CO_2 alone will give informa-

tion as to the general conditions which are being obtained in the furnace and the amount of excess air which is being admitted, but CO_2 records do not show whether combustion has been complete, or whether any appreciable amount of combustible gas is still present in the flue gases. Any increase of air above that required for complete combustion results in a loss of heat in the flue gases, as has been previously shown, but the presence of any appreciable proportion of unburnt combustibles results in a far greater loss. There is one critical point where the amount of CO_2 will be a maximum, with no combustibles still remaining unburnt. Any further reduction in the air supply will, while increasing the percentage of CO_2 , allow some of the carbon monoxide and hydrocarbons to pass away unburnt. This critical point usually occurs when the proportion of CO_2 reaches a figure of about 13 per cent., but the exact amount will depend on the condition of the fuel bed, the quality of the fuel, the design of the furnace and other local conditions, and the critical point where the most efficient results are being obtained in the furnace can only be determined by ascertaining the point where the presence of combustible gases is shown when the air supply is further reduced.

This point can be found by continuous analysis of the flue gases or by the installation of some instrument which shows automatically the presence of the combustible gases.

CHAPTER VII

FURNACES AND STOKERS

IN an earlier chapter fuels of various kinds have been referred to, and it is now proposed to mention the types of furnaces best suited to each kind of fuel.

Coal being the fuel most commonly found in use, we will commence by considering the types of furnace best suited for burning the different qualities of this fuel.

The furnace tube found in Lancashire and Cornish boilers is sufficiently well known to require little mention here, but the book would not be complete without referring to some of the more modern types of grates used in boilers of this class.

As regards hand-operated grates for boilers with Tubular Furnaces, these may be divided into two classes, viz., those with solid bars with air spaces between, and those with hollow bars through which the air for combustion is made to travel.

Fig. 11 shows a modern grate with solid bars and air spaces between.

The object aimed at in this furnace is to obtain a delivery of air through the fire bars at a rate as equal as possible over every square foot of the length and breadth of the grate.

The dead plate slopes downward, thus bringing the grate 3 inches to 5 inches lower than the ordinary level, which increases the room for combustion and the heating surface.

Beyond the bridge proper is a second fire bridge, so built as to ensure the flames having a more even

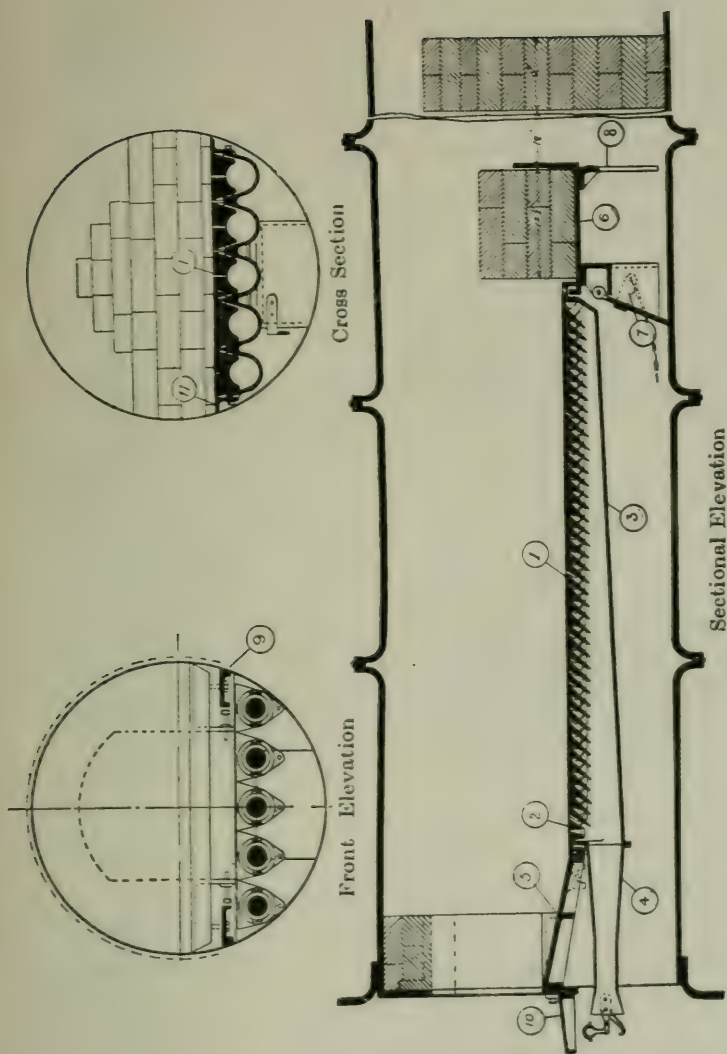


FIG. 11.—Solid Bar Grate with Steam Jet Forced Draught.

distribution round the furnace tube. Air is admitted to the chamber as required through the door shown under the first bridge to complete combustion in the chambers and prevent CO passing into the flues and back draught.

The furnace consists of five troughs arranged longitudinally as indicated in the illustration—each trough is fitted with a steam jet, working inside the Venturi casting, which draws in the air required for combustion. With steam at a pressure of 35 pounds per square inch at the jets, the resultant water gauge pressure is 0.5 inch under the bars.

Fig. 12 shows a hollow bar grate made by Wilton's Patent Furnace Co., and fitted to Lancashire boilers. This illustration shows the latest arrangement of steam jets, which has added considerably to the efficiency of the grate.

It is to be noticed that the bars are practically on the bottom of the furnace tube, thereby adding considerably to the combustion space and the heating surface.

It is claimed for this type of grate that any class of fuel from refuse upwards can be burned satisfactorily.

Experience has shown that for burning anthracite coals the plain level grate is the most serviceable whatever type of boiler is employed.

Such details as the size of coal, percentage of ash, rate of combustion, etc., will determine the width of bar—extent of grate surface and size of air opening.

Particulars in respect of these various points for coals from each of the different sources available would lead too far—they must be left to the personal experience of the furnace designer, and even so, some adjustment by the boiler attendant

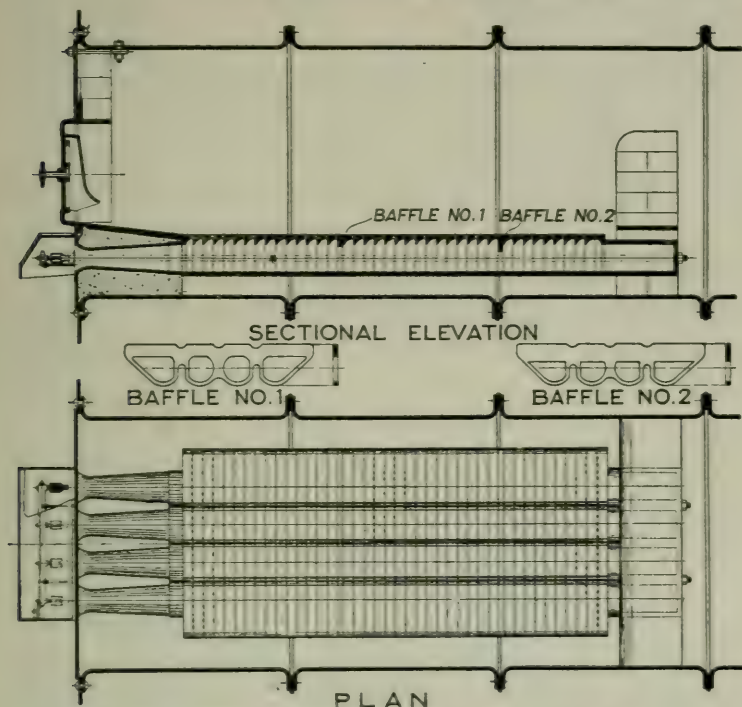


FIG. 12.—Wilton's Patent Forced Draught Furnace, 1925 pattern, fitted to Boiler Flue.

is usually required to suit the coal from the particular mine from which he draws his supplies.

Mechanical Stokers.—The benefit of mechanical stoking lies first in obtaining at regular intervals the feeding of small quantities of fuel so that the time between two charges is sufficient for the gases

to effect complete combustion; secondly, the avoidance of loss by the admission of excess air

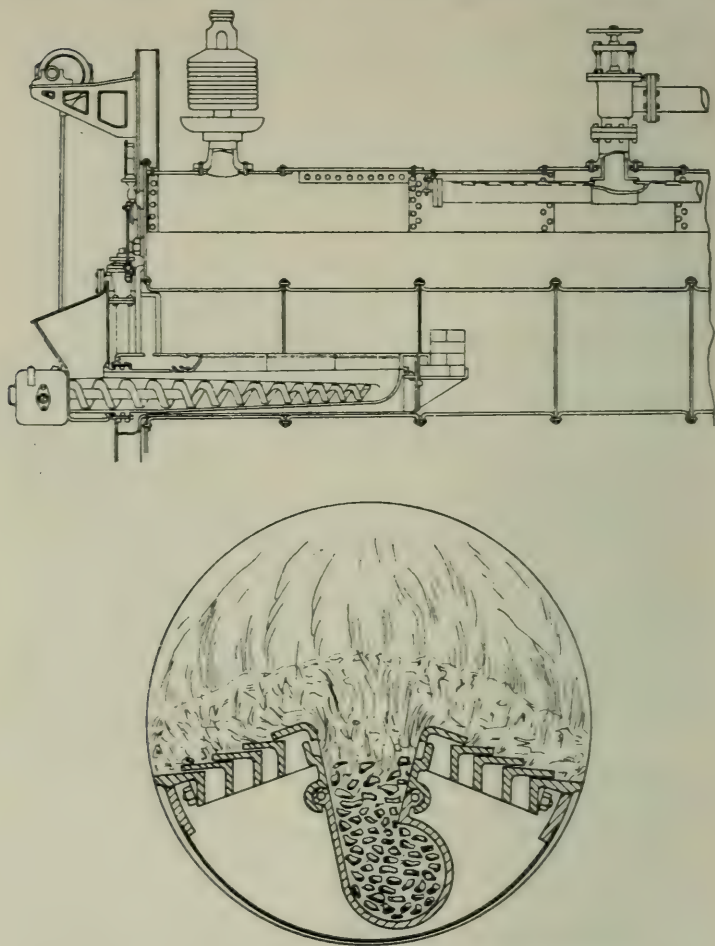


FIG. 13.—Illustration of Underfeed Stoker.

through opening the fire door when firing by hand; and thirdly, the reduction of human labour.

As regards the last point it must be remembered

that in a large modern water-tube boiler it would be practically impossible to hand-fire the large grates efficiently.

Mechanical stokers are divided into three classes, the underfeed, the overfeed and the chain grate.

In the underfeed type, the fuel is forced upward from underneath by a screw or plunger working along the centre of the length of grate. As the fuel is discharged on to the grate it falls over to the sides and then forms a long mound, thin at the sides and thick at the centre. This type of grate is illustrated in Fig. 13.

This form of stoker has decided advantages in dealing with certain classes of coal, particularly high-grade, hot, bituminous coals such as those found in the Barnsley district, as the metal is not in contact with the high-temperature layer of the fire-bed, but is protected by the low-temperature layer of coal before it reaches the initial stage of combustion when the hydrocarbons commence to be distilled.

The inclined overfeed type generally consists of a sloping grate, the highest part being at the point where the coal is fed, and the grate bars are generally so arranged that they may be periodically moved so as to feed the fuel along and down the surface.

As in the case of the underfeed type of stoker, the overfeed requires mechanical draught to ensure the best results.

Fig. 14 shows an overfeed stoker made by Edward Bennis and Co., Ltd.

The chain grate type of stoker consists of a chain grate on to which the fuel is fed at the front end of the boiler and which by its slow travel towards the bridge gives the fuel an excellent and undisturbed opportunity for complete combustion.

This form of grate is specially suitable for burning low-grade fuels, and it is generally so arranged that

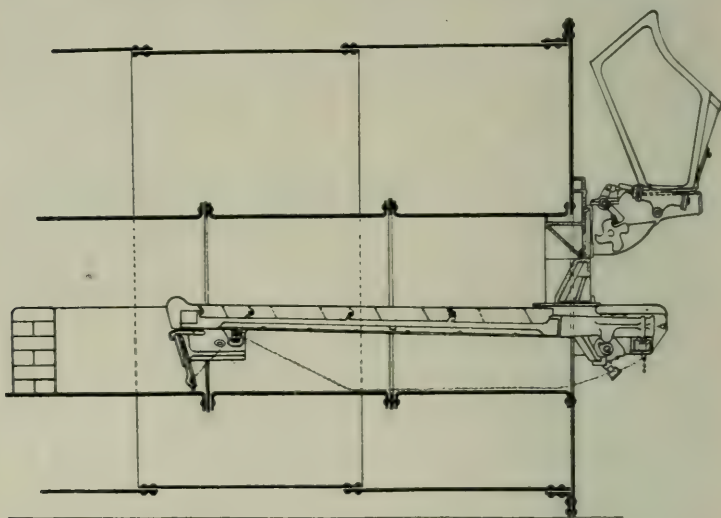


FIG. 14.—Overfeed type Stoker.
Ed. Bennis & Co. Ltd.

the fuel, at different points in its progress, receives its air supply in varying amounts and different pressures to suit the various stages of combustion, the air being supplied by mechanical means.

Fig. 15 shows a mechanical stoker of the chain grate type made by Babcock and Wilcox, Ltd., and divided into compartments so that the air pressure under the grate may be varied to suit different stages of combustion.

Comparisons between different forms of mechanical stokers demand that the conditions of test shall be identical.

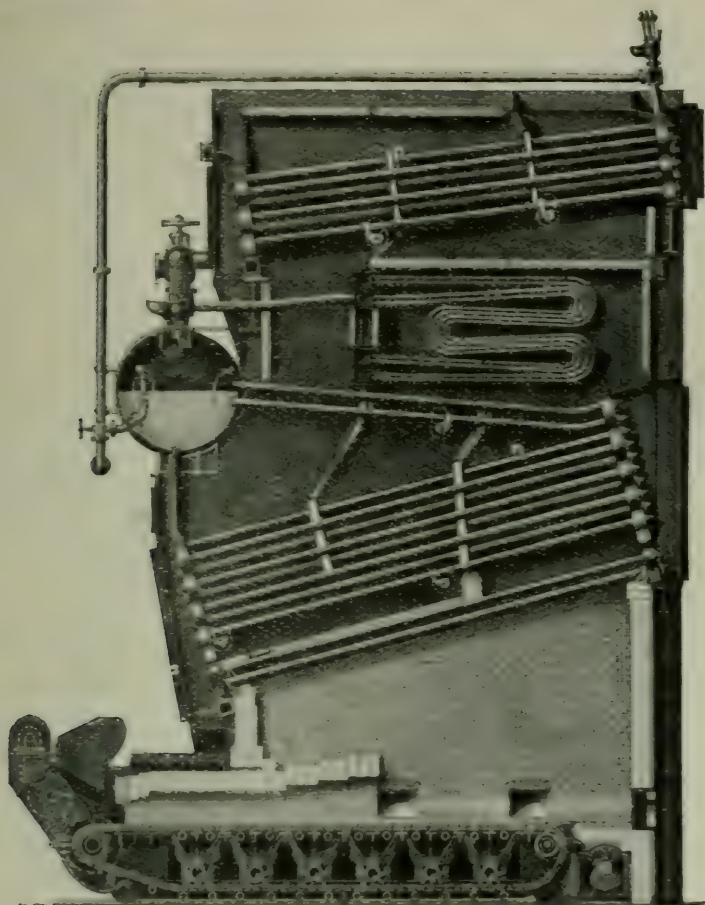


FIG. 15.—Babcock and Wilcox Boiler with
Compartment Chain Grate Stoker.

In all forms of mechanical stokers it must be possible to vary the rate of travel of the grate to suit the different qualities of fuel being burned,
5*

otherwise unburnt coal will be discharged at the end of the grate.

When low-grade fuels are employed having high percentages of ash, time must be allowed for the disengagement of the ash from the combustible matter.

Provision must also be made to prevent clinker growths, and particularly is this so with stokers of the underfeed type. In the absence of such provision, a reverberatory action of flames is set up under the clinker, throwing back hot gases, with a destructive effect on the stoker.

The mechanical stoker possesses many advantages, but these can only be realised when the stoker is properly suited to its particular work and is intelligently operated.

Coke.—This fuel can only be burned satisfactorily on a plain level grate, and the form of grate bar requires to be carefully considered. Coke requires a strong draught for combustion, but it must be remembered that the heat from coke is local, and unless precautions are taken, the fire bars will suffer. To minimise this risk water in the ash-pits or steam jets should be used.

Wood.—Wood fuel packs loosely in the furnace, thus offering little resistance to the passage of air, and it is not necessary that the grate surface should be large, although an adequate combustion space is essential. The area of the furnace varies with the nature of the wood, some wood being of higher calorific value than others.

In some parts of Australia, India, Russia and South America wood is used in the form of logs. If, however, it is fired as brushwood or in the form

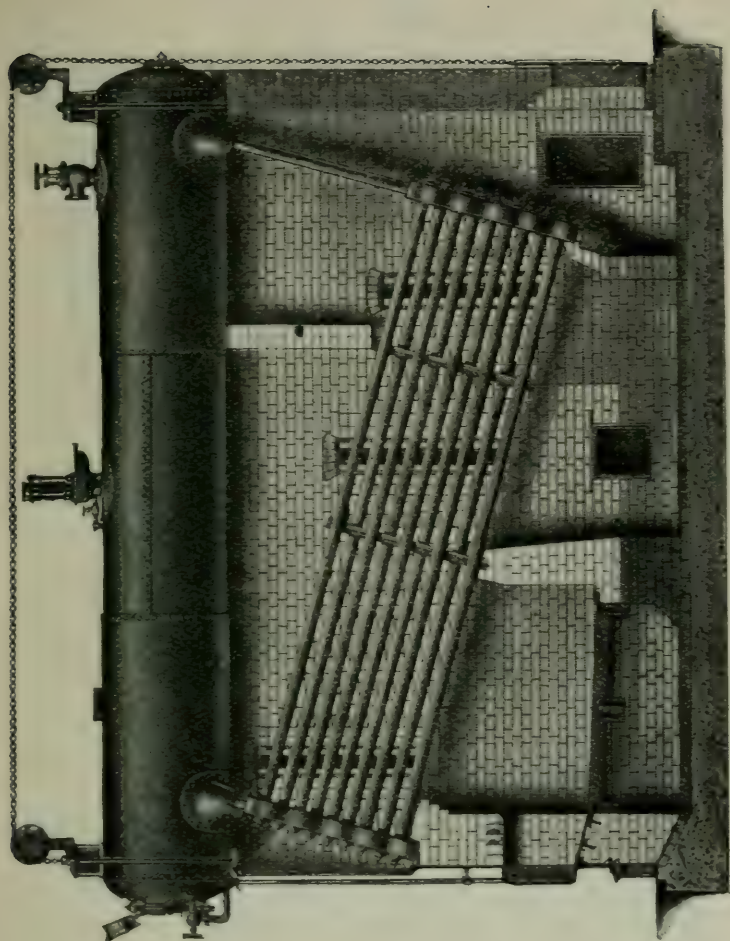


FIG. 16.—Babcock and Wilcox Boiler Arranged for Burning Ordinary Fuel. (Wood in Log or Chips.)

of sawdust, either an inclined or a step grate furnace is best.

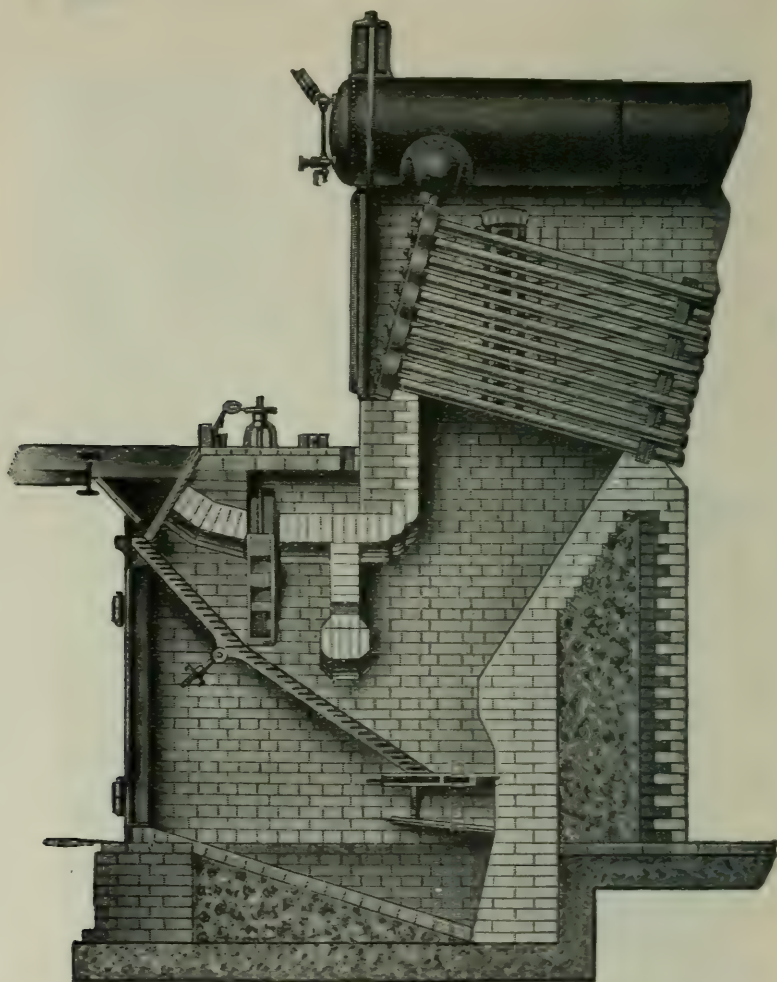


FIG. 17.—Babcock and Wilcox Boiler with Step Bar Grate for Burning Lignite.

In order to obtain sufficient combustion space, it is frequently necessary to extend the furnace in front of the boiler.

Fig. 16 shows a furnace for burning ordinary wood fuel.

Lignite.—Fig. 17 shows a Babcock and Wilcox boiler with special grate for burning lignite.

The low calorific value of this fuel necessitates a furnace with large grate area and preferably without fire doors, for obviously the great quantity of lignite required increases the frequency of firing.

From the illustration it will be seen that the grate is stepped, and owing to the inclination the fuel is self-feeding.

A large hopper may be provided and a large fire bar surface and combustion chamber secured, whilst the spaces between the bars or steps allow the large quantity of refuse—which generally forms slag or clinker—to be readily removed with a slice.

With a good draught of say 0·5 inch W.G. 30 pounds of lignite may be burned per square foot of grate per hour.

Some of the German lignite coals having a comparatively high calorific value of, say, 9000 B.Th.U.s per pound can be burned satisfactorily on a chain grate stoker, although, as already stated, it is usual to employ a stepped grate.

Bagasse.—This fuel, which is the refuse from the sugar-cane and is fully described in a previous chapter, was in the earlier days dried and fired in ordinary furnaces, but as the output of sugar-mills increased and the extraction became greater, furnaces were introduced to burn “green” bagasse.

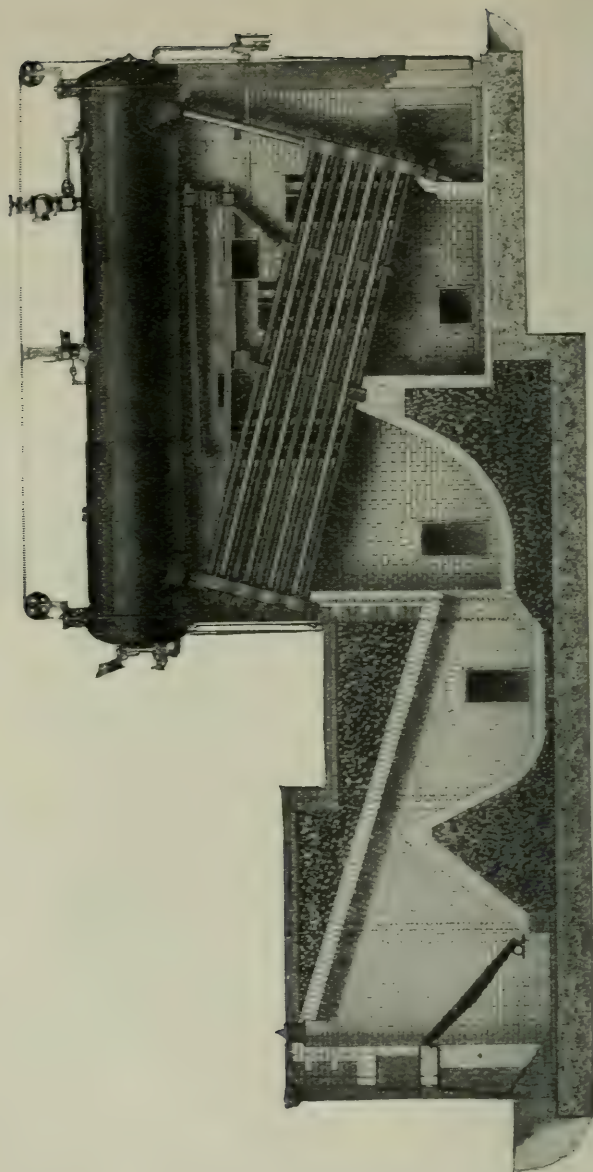


FIG. 18.—Babcock and Wilcox Boiler Fitted with Superheater and Sloping Bar Furnace.
For Burning Green Bagasse with Natural Draught. Used in Trinidad and Jamaica.

The best results are obtained by burning the bagasse in large masses, for instance, one size of furnace adopted is for consuming 9 tons of bagasse per hour.

The form of grate and style of furnace depend very largely on the conditions obtaining in the different sugar-growing countries. For instance, in Java, Peru and Mexico, Trinidad and Jamaica, the sloping bar and stepped grate are commonly found, whilst in Tucuman the level bar grate with forced draught is employed.

In all cases large combustion chambers must be provided with suitable doors for cleaning out the furnaces.

Fig. 18 shows a boiler fitted with step grate furnace with air heating passages in side walls for burning "green" bagasse with natural draught.

Oil Fuel.—The three principal factors governing a satisfactory oil-burning furnace are large combustion space, a good atomiser and a suitable air supply.

There are a number of different types of oil burners now on the market, but the method of atomising oil at present most generally in favour is by steam taken into the burners. The number of burners required for a boiler of given size will, of course, vary according to the design and type of burner employed.

Economy of steam may be obtained by forcing the oil into the burner under pressure.

In some low-pressure installations, air is used instead of steam for atomising the oil.

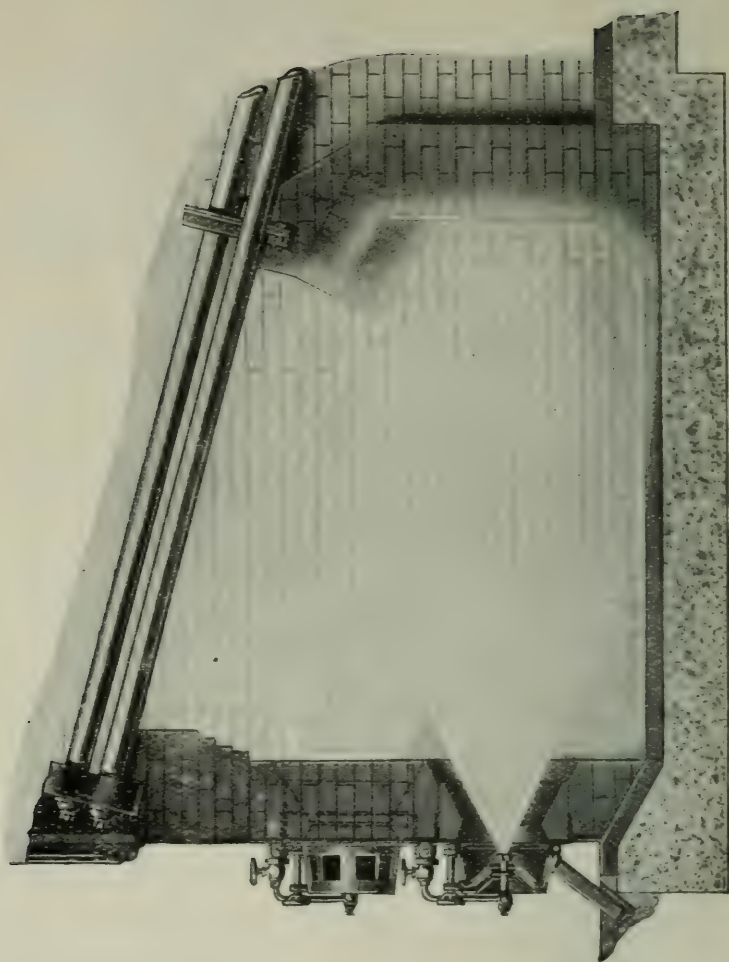


FIG. 19.—Babcock and Wilcox Boiler, showing Furnace for Burning Oil Fuel Only.

Under favourable conditions, petroleum is smokeless, does not deposit soot on the heating surfaces, and requires practically no attention.

Fig. 19 shows a Babcock and Wilcox boiler with furnace for burning oil fuel only.

As in the case of powdered and also gaseous fuels, the combustion chambers must be of ample dimensions and lined with refractory materials. Liquid fuel can be adopted on any form of boiler with very slight modifications, and in some instances without any alterations whatever beyond the provision of an additional bridge or baffle. In this way it is possible to change from liquid to hard fuel at the shortest notice or at any time to revert to liquid fuel.

Amongst well-known oil burners mention may be made of the "Kermode," the "Carbogen," the "Meyer," and the "Korting" and others.

In the case of the Meyer burner, manufactured by Smiths Dock Co., the installation is of the pressure type, that is, the oil is atomised by means of pump pressure only, forcing the oil through a specially constructed atomiser or burner, and no steam or air jets are employed to break up the fuel.

The oil is drawn through a filter and then through a heater, when the temperature is raised to from 180° to 320° F. according to the class of oil which is being dealt with.

A second filter is interposed between the heater and the burners.

The oil delivery pipes across the boiler fronts

are so arranged with valves that, when lighting up, the oil is bye-passed back to the suction side of the pumps, instead of to the burners, until the desired temperature is reached.

When the ignition point is reached the oil is ignited by means of a common torch inserted through a small door provided in the furnace front for the purpose.

Air for combustion is admitted through openings round the burner, and the air passing through the passages absorbs heat, thereby ensuring the proper combustion of the fuel.

Powdered Fuel.—The burning of powdered fuel presents many difficulties, but rapid advances have been made in recent years, and at the present time a large number of important installations are at work giving excellent results.

The powdered fuel being blown into the furnace is ignited and complete combustion takes place instantaneously; a maximum flame temperature is produced without loss of thermal value or unconsumed carbon.

The flame temperature of the fuel obtained in practice is very high owing to the fact that the excess air used for combustion is very small.

With 20 per cent. to 25 per cent. excess air the maximum temperature will be between 1800° C. and 1900° C., and one of the first difficulties to be overcome is to render the furnace lining capable of withstanding this high-temperature flame.

Various refractory materials exist, such as silica, alumina, bauxite, and chromite, whose melting

points are from 1600°C. to 2180°C. , and it will be seen that the temperature of a pulverised coal flame is well up to these figures.

In considering the life of combustion chamber linings it must not be overlooked that difficulties may occur due to the fluxing action of iron oxide and alkalis, always found in the ash of coals, or the destructive action of lime or calcium oxide and alumina in the ash, which will readily combine with silica at high temperatures.

To avoid these difficulties, the combustion chamber should be arranged in such a manner as to prevent the direct impingement of the flame on the refractory lining.

The exact arrangement of refractory linings will depend largely on the class of fuel used. For instance, when burning anthracite or pulverised coke, it is essential in some circumstances to arrange refractory arches or return walls so that the flame will beat back on the incoming stream of fuel and thus maintain continuous ignition.

A very important point in designing the combustion chamber is that relating to the velocity of the gases. In the first place, the velocity must be sufficiently high to maintain the particles of pulverised fuel in suspension during the whole period of combustion. The smaller the combustion area available the finer the degree of pulverisation necessary, or the finer the degree of pulverisation the lower will be the permissible velocity of gases in the furnace.

If the velocity through the chamber be too high,

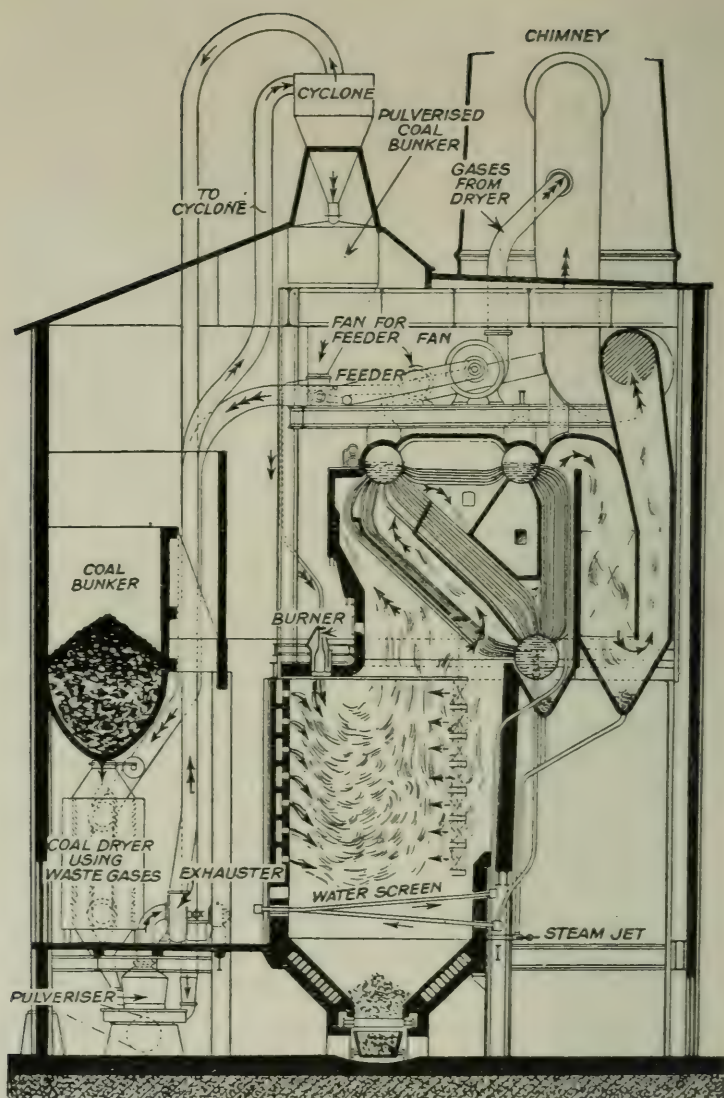


FIG. 20.—Arrangement of Water Tube Boiler with “Lopulco” System of Powdered Fuel Firing (Vickers and International Combustion Engineering Co.).

the burning particles of fuel will be carried right through the combustion chamber and into contact with the end wall, before complete combustion is effected and whilst the ash content is at its maximum temperature and therefore perhaps in a plastic state.

The ash particles together with the remaining unburnt fuel will then adhere to the furnace end wall or boiler tubes and in this manner a coating of ash and slag will be built up.

Any ash in the actual flame will be in a semi-fluid or fluid state, in which condition it will readily adhere to other ash particles or to the furnace wall or boiler tube. It is therefore necessary to remove ash from the zone of highest temperature as soon as the combustible matter has been consumed. This can be done by allowing the ash to pass to, or fall on coolers, when it will remain in a form in which it can be handled without difficulty.

Some makers of powdered fuel plant claim that no coolers are necessary, but certainly some provision must be made to deal with slag which is formed, and in any case large cleaning doors are essential.

Fig. 20 shows a boiler arranged for burning powdered fuel.

Various forms of burners exist for mixing the fuel and air, and one of the most efficient types in general use is that known as the Lopulco Feeder Mixer. In practice, air is supplied at 6 to 8 ounces pressure and enters a jacket surrounding the delivery end of a screw feed. At this point the

mixed coal and air is given a whirling motion by means of paddle blades, which thus assist the intimate mixing of the fuel and air for combustion. Secondary air for combustion is admitted through horizontal passages in the front and side walls, and

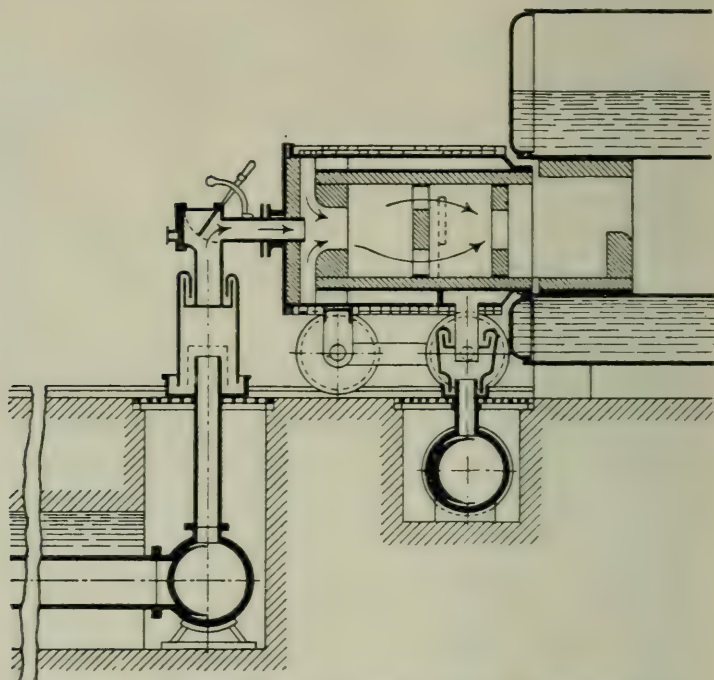


FIG. 21.—Arrangement of Furnace for Gas-fired Lancashire Boiler.

the temperature of the air entering the combustion chamber through the front wall is thereby raised.

Gaseous Fuel.—Blast furnace and coke oven gas are the principal fuels employed under this heading. Special large combustion chambers are necessary, lined with refractory materials with one or two bridges. A long flame of high temperature

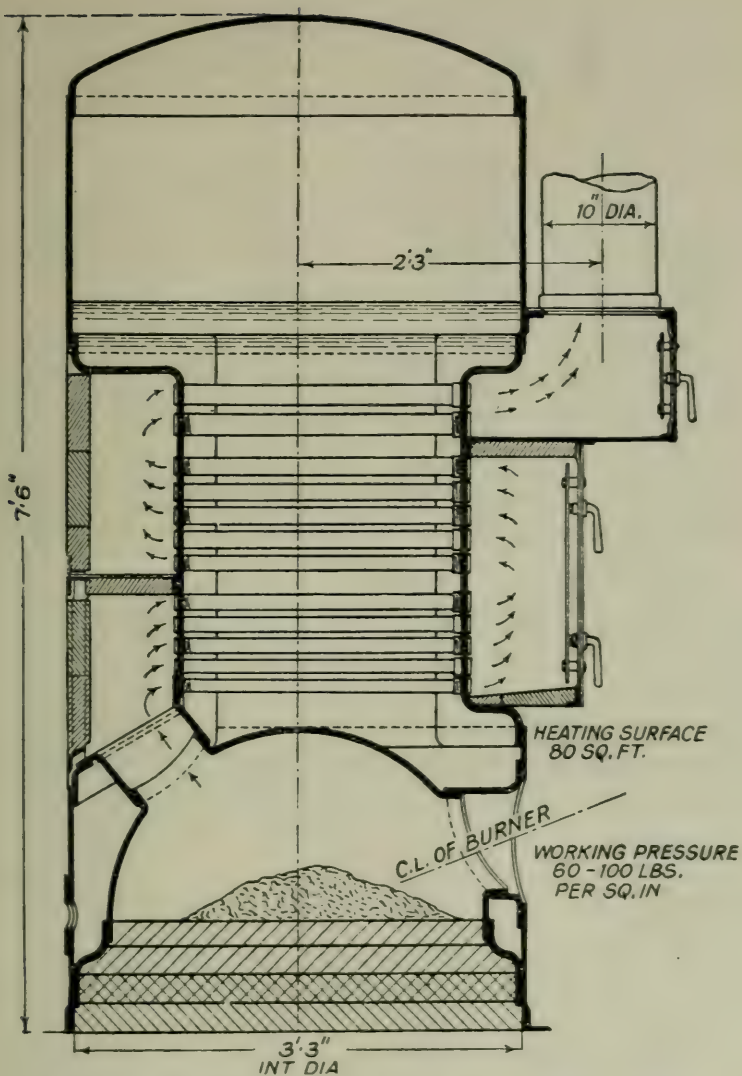


FIG. 22.—Arrangement of Gas-fired Vertical Type Boiler.

is obtained, and care must be taken that it does not impinge on boiler tubes or furnaces, hence the provision of one or more bridges in the combustion chamber.

In order to obtain sufficient combustion space when firing Lancashire boilers with gas, it is necessary to build brick chambers in front of the boiler (see Fig. 21).

One of the most recently introduced gas-fired boilers is that by British Furnaces, Ltd., of Chesterfield, a boiler incorporating the principles of surface combustion.

A boiler of Cochrane type is used for the purpose with certain alterations to adapt it for gas firing (see Fig. 22).

In the combustion chamber the usual grate for coal firing is replaced by a refractory bed. The upper part of the boiler consists of two or three passes of tubes and can be compared to a waste heat boiler. On a recent test on a gas-fired boiler of this type a net efficiency of 88.34 per cent. was obtained.

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